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Geobarometric analysis of Amphiboles of Putteti Igneous Suite, Kanyakumari District, Tamil Nadu, South India

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Abstract

Putteti Igneous Suite, located south of Achankovil Shear Zone in Southern Granulite Terrain (SGT) of South India, is known for its compositional diversity and presence of ubiquitous zircon megacrysts. Syenite and pyroxenite, which occur as alternate magmatic layers form the major lithounits of the suite along with a hybrid rock. Alkali feldspars, perthite and pyroxenes form the major minerals in syenite, while the pyroxenite is rich in clinopyroxenes with a few grains of perthite. Minor amounts of plagioclase, amphibole, micas, zircon, apatite and opaques are also noticed in syenite. The late magmatic stage in the suite is characterized by a number of pyroxenite and syenite bands that criss cross the syenite body at places. One of the syenite-pyroxenite contacts is characterized by an abundance of amphiboles and phlogopite. Electron micro probe studies reveal the presence of calcic amphibole (edenite) and magnesium-rich mica, phlogopite. Detailed geobarometric studies of amphiboles give a mean pressure and depth of crystallization of 3.36Kb and 12.5Km respectively for the suite.

Keywords: Putteti igneous suite, syenite, amphibole, geobarometry

1. Introduction

Advanced analytical techniques such as ion probe or electron microprobe of the rocks not only give the chemistry of the minerals present in them but also provide other vital information regarding their origin. Pyroxenes and amphiboles in igneous rocks are widely used to determine the temperature, pressure and depth of formation of the rocks. Although pyroxenes and amphiboles contain similar oxides and trace elements, their structure and temperature of formation differ even in the same rock. Amphiboles, which contain OH⁻ radical, indicate the presence of volatiles in the magma. Amphiboles are considered to be better geobarometers and are useful in calculating the depth of formation. Here an attempt has been made to decipher the pressure and depth of formation of an alkaline igneous suite near Putteti, Kanyakumari, Tamil Nadu using amphiboles.

Estimation of the conditions of crystallization of an igneous body can provide evidence of its evolutionary history (Christofides *et al.*, 2007) [1]. The geochemical observation on the petrogenesis of Putteti Alkaline Suite points to the anhydrous nature of parental magma in the initial stages of crystallization of the members of the suite, especially syenite and pyroxenite. However, the presence of a number of pegmatitic veins of syenite and pyroxenite in the suite is believed to be products of later stages of the crystallization; this points to the existence of vapour phase in the melt. The appearance of amphibole and phlogopite along the contacts of these rocks also support this argument. Amphibole, although present in small amount in Putteti rocks, is used in this study for deciphering the condition of crystallization of the suite.

2. Geologic setting

The study area is located at Putteti, near Karungal in Kanyakumari district of Tamil Nadu, South India, where a syenite body has been noticed (Fig.1) (Odom, 1982; Nair and Santosh, 1985; Santosh *et al.*, 1989; Rajesh, 2003; Miyasaki and Santosh, 2005) [2, 3, 4, 5, 6]. Detailed geologic investigations have revealed that it is an alkaline suite with two extreme members, namely syenite and pyroxenite, and a hybrid rock (Rajesh, 2003; Anjana, 2019) [5, 7]. Based

on colour and texture, different varieties of syenite can be distinguished in the suite- grey and white syenites, and coarse and very coarse (pegmatitic) syenites.

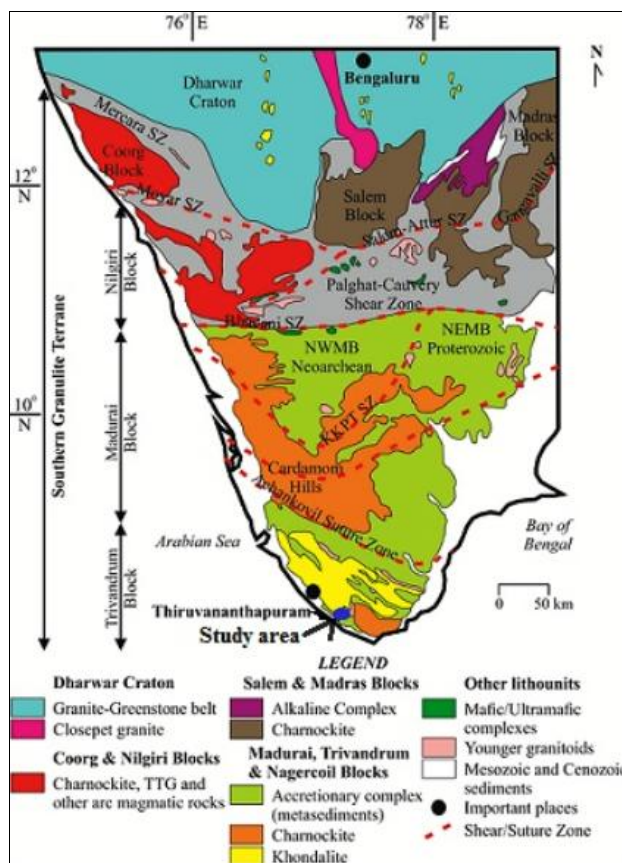


Fig 1: General tectonic frame work of Southern Granulite Terrain indicating the location of the study area (modified after Santosh et. al, 2015)^[8]

However, their distribution and smaller areal extent prevent their mapping as separate entities (Anjana, 2019)^[7]. Within the syenite, pyroxenite is found as either parallel or criss-crossing late phase mafic bands. The hybrid rock has a cumulus nature with equal proportions of feldspar and pyroxenes. Syenite has feldspar as the major mineral constituent, as orthoclase in grey syenite and as perthite in

white syenite. Clinopyroxenes are the major mafic minerals in both syenite and pyroxenite; a few grains of biotite and amphiboles are also found. Accessory amount of zircon, sphene and quartz are also noticed. Granulites and garnetiferous biotite gneiss and their variants form the major country rocks.

Although amphibole grains occur in minor amounts in different varieties of syenite, it is abundant along the syenite-pyroxenite contact; the grains are associated with clinopyroxenes (augite and diopside) and phlogopite.

3. Methodology

In the last several decades a number of studies on the occurrence of zircon megacrysts in the syenite of Putteti have been carried out (Odom, 1982; Santosh *et al.*, 1989; Rajesh, 2003; Miyasaki and Santosh, 2005)^[2, 4, 5, 6]. Most of them have considered it as a single NNW-SSE trending syenite pluton. In the present study intense field mapping has revealed a few new outcrops that have been exposed due to the recent quarrying activities in an around Putteti. A few of these outcrops are similar to the already described syenite body; but some of the newly found syenites differ in texture and mineralogy. By combining the newly found outcrops with the earlier body, a revised geologic map has been prepared (Fig.2). It also shows the presence of an ambiguous rock (peperite?). The earlier described single syenite body is exposed near the Putteti temple, near Karungal town (Fig.3).

The rock samples collected during field study were subjected to detailed petrographic examination. Thin sections were used for both microscopic and Electron Microprobe Analysis (EPMA) in the Department of Geology, University of Kerala and in the Advanced Facility for Microscopy and Microanalysis (AFMM) of Indian Institute of Science, Bangalore, respectively. EPMA was performed with acceleration voltage of 15 keV and beams current of 12nA. For computing the geobarometry of the suite, selected grains of amphiboles in a major syenite-pyroxenite contact were used. The major minerals (both amphiboles and micas) present in this contact were studied for obtaining the original chemical nature of the magma and depth of crystallization of the suite.

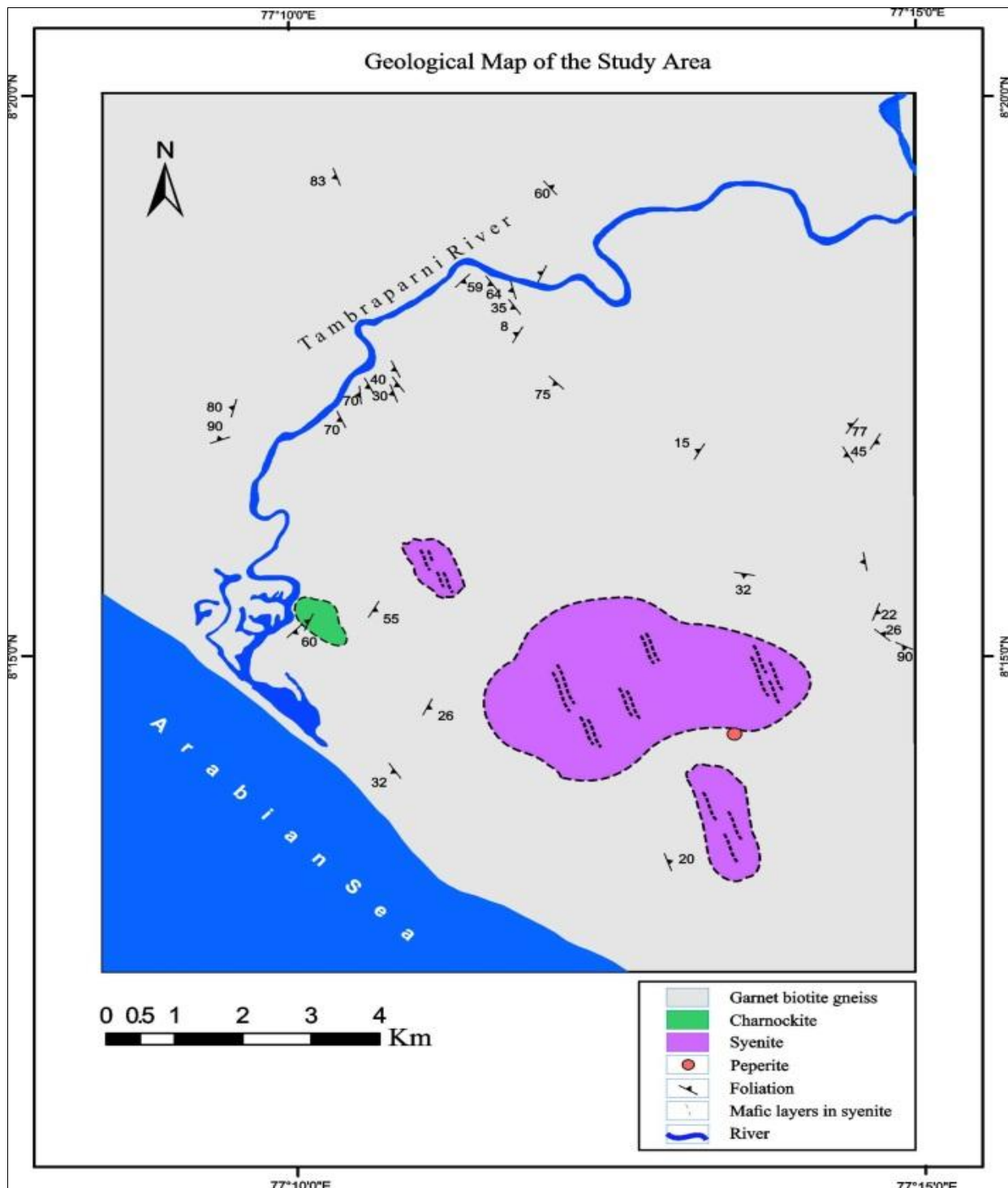


Fig 2: Geological Map of Putteti Igneous Suite, Tamil Nadu

4. Result and Discussion

4.1 Field relations

The host rocks of the syenite body, the gneisses (Fig.4) and granulites, are considered to be the southward extension of the Kerala Khondalite Belt (KKB), which was later renamed as Trivandrum Block (Collins *et al.*, 2014) [9]. The crystalline rocks in Trivandrum Block had formed under amphibolite to granulite facies metamorphism (Chetty, 2016) [10]. Putteti syenite is thought to have intruded the existing lineaments/fault zones (Santosh *et al.*, 1989; Rajesh, 2003; Miyasaki and Santosh, 2005) [4,5,6], the absence of contact aureole or chilled margin in and around the outcrops, points to a magmatic activity in the later stages of metamorphism in the terrain.

As mentioned earlier, syenites are the dominant intrusive members of the suite with two colour variants- grey and white with their pegmatitic counterparts (Fig.5). The similar texture and mineralogy of the syenite variants points to a single parental magma for their origin. The pegmatitic syenite variants could have evolved in the late stage of formation of the members of the suite as a result of very slow cooling (Anjana *et al.*, 2019) [11].

Pyroxenite is a dark colored, heavy, highly fractured, very coarse-grained rock with abundant pyroxenes and phlogopite (Fig.6). Pyroxenes are identified by their short prismatic crystals, dark green colour, pearly or sub-vitreous luster and moderate hardness. Dark brown flakes of phlogopite are sprinkled all over the rock.

Hybrid rock, which has near equal proportions of orthoclase and pyroxenes, might be a resultant product of mixing and mingling of the two members, syenite and pyroxenite (Fig.7). It has limited occurrence and shows typical cumulate texture in which the fine to medium grained euhedral grains of pyroxenes are embedded in a matrix of orthoclase of syenite. The layering of ferromagnesian minerals, especially pyroxenes, in the rock also supports a magmatic origin. The layering could be due to gravity settling of the heavy ferromagnesian minerals. The layering is also indicative of gravity settling and fractional crystallization that existed during the formation of the components of the rocks.

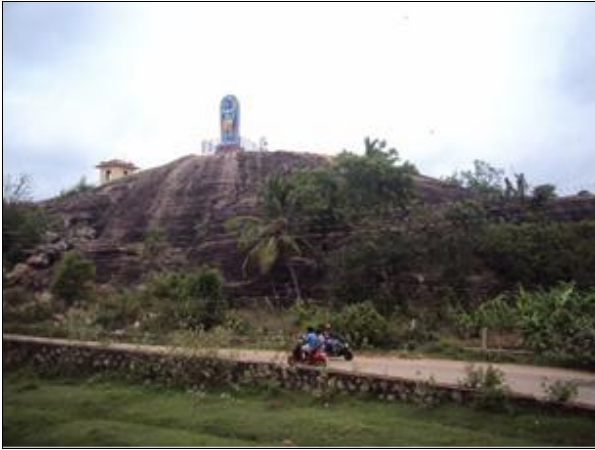


Fig 3: Main syenite hillock at Putteti- distant view from West



Fig 4: Closer view of garnetiferous biotite gneiss with well-developed banding (plan view)



Fig 5: A small vein of pyroxenite in grey pegmatitic syenite



Fig 6: Pyroxenite bands in syenite



Fig 7: Hand specimen of hybrid rock with pyroxene cumulates



Fig 8: Phlogopite vein at syenite-pyroxenite contact

The presence of a number of syenite and pyroxenite veins, that criss- cross the suite, might be products of the last stages of igneous activity. Some of these veins with irregular borders extend considerably and might have exchanged felsic and mafic components. A larger vein of syenite-pyroxenite is noticed at the contact in the major exposure, the contact border is characterized by the presence of phlogopite and amphiboles (Fig. 8).

4.2 Petrography

In thin sections syenite shows a holocrystalline, hypidiomorphic, medium to coarse grained, equigranular texture with interlocking grains of alkali feldspars and perthite, pyroxenes and minor amounts of plagioclase, amphibole, mica (phlogopite), zircon, apatite and opaques (Fig.9). Grey syenite is characterized by abundance of

orthoclase feldspar (69.58%) and pyroxenes (19.45%) and a few grains of olivine (restricted occurrence), perthite and plagioclase. Most of the orthoclase grains are nearly euhedral; some grains show signs of perthitization with equally spaced, hair line intergrowth lamellae. Euhedral grains of clinopyroxenes (augite, diopside and hedenbergite) are seen intergrown between grains of orthoclase. The more important accessory minerals present include zircon, apatite, sphene, magnetite, ilmenite, chevkinite and sulphides. Zircon is seen as independent grains and as inclusions in other minerals, especially in feldspars. Zircon grains show twinning and overgrowth (Fig.10).

Under the microscope, pyroxenite shows equigranular, coarse grained interlocking texture and is composed mainly of clinopyroxenes (70.48%) - augite, diopside and hedenbergite (Fig.11) with minor amounts of plagioclase (10.05%), orthoclase (7.03%), biotite and accessory apatite and zircon. The pyroxenes are uneven, highly fractured and dull looking with high relief and exhibit higher order interference colour. Some augite grains preserve hourglass structure. Orthoclase and small laths of plagioclase are interstitial to pyroxenes; orthoclase is occasionally perthitized (bead type).

Hybrid rock is holocrystalline with alternate layers of syenite and pyroxene with a cumulate texture (Fig.12). Major clinopyroxenes identified include augite, diopside and hedenbergite; some amount of plagioclase, hornblende and biotite are also present. Pegmatitic variety of syenite has large grains of orthoclase interwoven between small grains of augite and diopside (Fig.13).

A well-developed zone of syenite-pyroxenite contact was also subjected to microscopic studies. Here the major minerals identified include hornblende and phlogopite along with orthoclase and pyroxenes (Fig.14). The minerals showing preferred orientation and are aligned parallel to the length of the pyroxenite vein.

4.3 Mineral chemistry

A few minerals in a syenite- pyroxenite contact zone in a major exposure of Putteti have been subjected to EPMA. Amphibole and mica are found along with orthoclase and pyroxenes in this zone. As amphiboles are very useful for geobarometric analysis, that part of the rock with abundant amphiboles was used for mineral chemistry. The details of the mineral data and their interpretations are given in the following sections.

4.3.1 Amphibole

The mean content of hornblende found in the contact zone are SiO_2 (43.54%), Al_2O_3 (8.10%), CaO (10.88%), MgO (12.04%), FeO (14.87%), Na_2O (1.93%) and K_2O (1.75%) (Table1). The chemistry indicates the mineral to be Edenite, a calcic amphibole as per the classification of Leake *et al.*, (1997) [12]. The (Na+K) (A) vs Ca diagram for amphiboles also confirms its calcic nature (Fig. 15). Moreover, in $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ vs Si diagram, these amphiboles are located in the field of edenite (Fig. 16).

The mineral chemistry of amphiboles indicates its calcic nature with magnesio-hornblende composition (Edenite). Calcic amphibole is a common solid-solution component in intermediate and felsic igneous rocks; its composition is sensitive to pressure, temperature and bulk composition,

making it a potentially useful phase for the direct estimation of the conditions of magmatic crystallization (Blundy and Holland, 1990) [13].

4.3.2 Mica

The mean composition of micas from EPMA shows that they are rich in SiO_2 (40.93%), Al_2O_3 (10.77%), MgO (18.18%), FeO (10.42%), K_2O (10.15%) and poor in Na_2O (0.13%) and CaO (0.05%). The high content of Mg makes it a Phlogopite (Deer *et al.*, 1997) [14]. The field observation is substantiated by EPMA study (Anjana, 2019) [7].

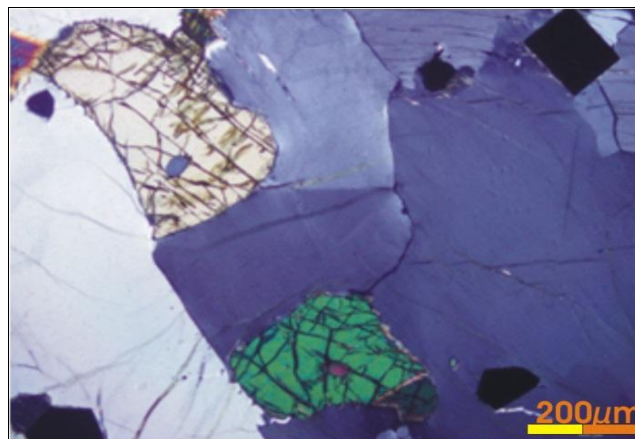


Fig 9: Hypidiomorphic texture in grey syenite (XPL)

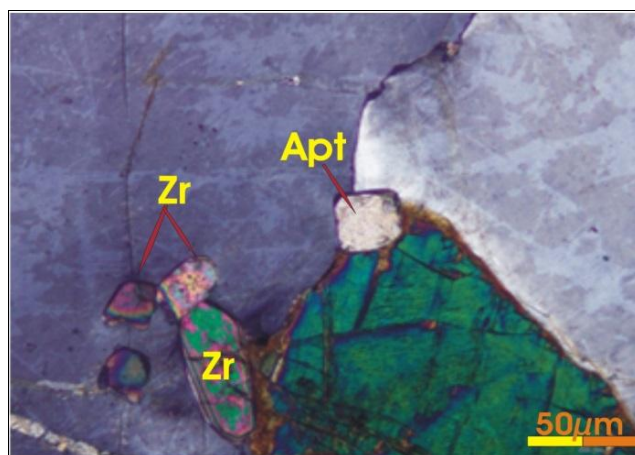


Fig 10: Overgrowth in zircons. Also note the apatite grain (XPL)

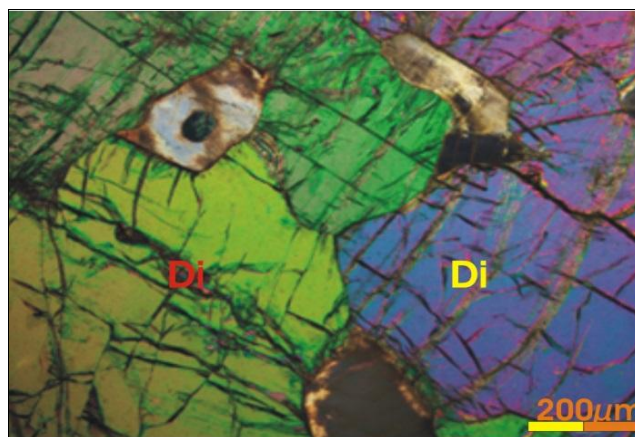


Fig 11: Diopside showing typical hourglass structure in pyroxenite (XPL)

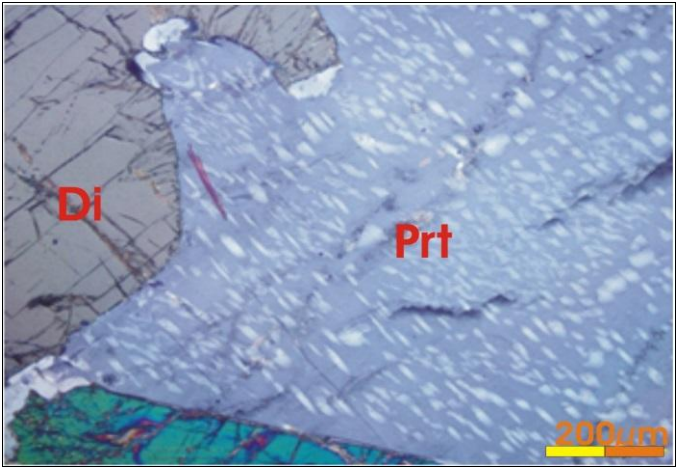


Fig 13: Photomicrograph of pegmatitic syenite with perthite and diopside (XPL)

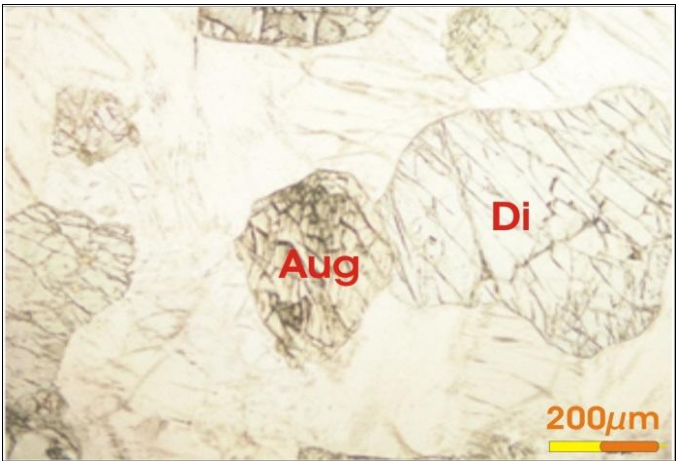


Fig 12: Cumulate texture in syenite-pyroxenite contact (PPL)

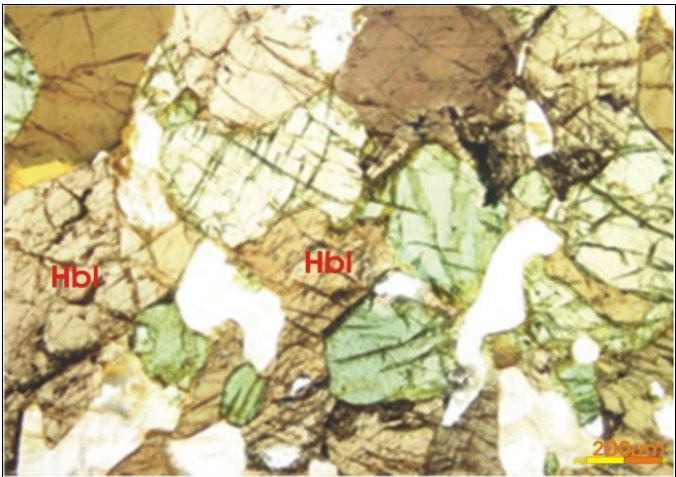


Fig 14: Concentration of hornblende at syenite-pyroxenite contact (PPL)

Table 1: Mineral chemistry of amphiboles in syenite-pyroxenite contact

PU-4	Amphibole from Syenite- Pyroxenite contact						
Major oxides (wt%)							Mean
Sample	1	2	3	4	5	6	
SiO ₂	43.403	43.798	43.691	43.412	43.12	43.786	43.535
TiO ₂	0.964	1.001	1.17	1.061	1.065	0.941	1.034
Al ₂ O ₃	8.079	8.075	8.293	7.999	8.008	8.149	8.101
FeO	14.606	14.855	14.425	15.511	15.101	14.734	14.872
MnO	0.427	0.464	0.549	0.507	0.504	0.501	0.492
MgO	12.074	11.828	11.974	12.128	12.195	12.03	12.038
CaO	11.215	10.898	10.804	10.72	10.61	11.053	10.883

Na ₂ O	1.852	1.907	1.869	2.053	2.017	1.879	1.930
K ₂ O	1.694	1.754	1.762	1.745	1.787	1.75	1.749
Total	94.314	94.58	94.537	95.136	94.414	94.823	94.634
Cations based on 22 oxygen							
Si	6.699	6.737	6.704	6.630	6.626	6.714	6.685
Al (iv)	1.301	1.263	1.296	1.370	1.374	1.286	1.315
Al (vi)	0.169	0.201	0.204	0.070	0.076	0.187	0.151
Fe(iii)	0.311	0.326	0.369	0.600	0.606	0.349	0.427
Ti	0.112	0.116	0.135	0.122	0.123	0.109	0.119
Fe(ii)	1.574	1.585	1.482	1.381	1.334	1.540	1.483
Mn	0.056	0.060	0.071	0.066	0.066	0.065	0.064
Mg	2.778	2.712	2.739	2.761	2.794	2.750	2.756
Ca	1.855	1.796	1.776	1.754	1.747	1.816	1.790
Na	0.554	0.569	0.556	0.608	0.601	0.559	0.574
K	0.334	0.344	0.345	0.340	0.350	0.342	0.343
Total	15.742	15.709	15.677	15.702	15.698	15.717	15.707
X Mg*	0.638	0.631	0.649	0.667	0.677	0.641	0.650
Mineral Name							Edenite

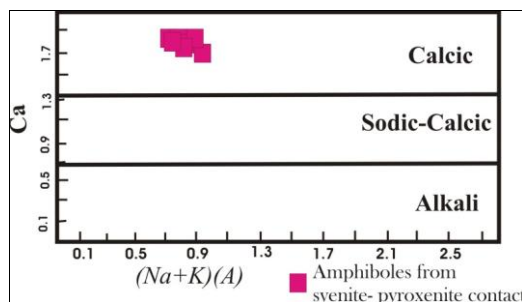


Fig 15: (Na+K) (A) vs Ca diagram for amphiboles in syenite-pyroxenite contact

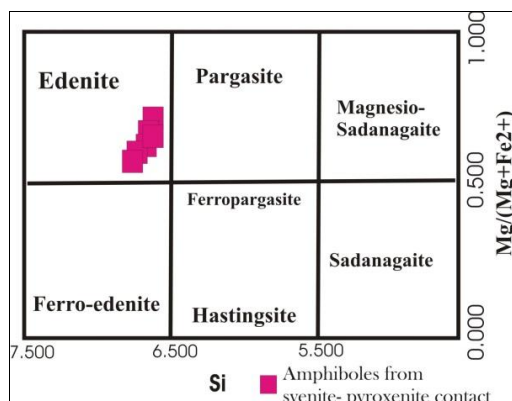


Fig 16: [Mg/(Mg+Fe)] vs Si diagram for amphiboles in syenite-pyroxenite contact

4.4 Pyroxenes

Clinopyroxenes are the major mafic mineral components in syenite, hybrid rock and pyroxenite. They are rich in SiO₂ (51.02-52.61 wt%), MgO (11.36-13.18 wt%), CaO (21.95-22.63 wt%) and FeO (6.30-10.26 wt%) and poor in Al₂O₃ (1.12-1.49 wt%), Na₂O (0.25-0.39 wt%) and K₂O (0-0.02 wt%). The mineral chemistry points to the calcic nature of pyroxenes- augite is the dominant pyroxene followed by diopside and hedenbergite (Anjana *et al.*, 2019) [10].

4.5 Geobarometry

The pressure and depth of formation of syenites is deciphered using selected mineral chemical data of amphiboles from EPMA. Pressure estimates were made using the Al-in-amphibole geobarometer. Larger laths of amphiboles are mainly confined to the syenite-pyroxenite contact. Hence the geobarometric calculations, using the method of (Hammarstrom and Zen (1986) [15], Johnson and Rutherford (1989) [16], Hollister *et al.*, (1987) [17] and Schmidt (1992) [18], have been done on the EPMA data of edenite from the rock of syenite-pyroxenite contact (Table 2); the mean pressure obtained is 3.36Kb.

Based on the same mineral data, the mean depth of formation of the rock has been computed (Tulloch and Challis, 2000) [19] as 12.5 Km. This indicates that the later stages of the alkaline suite of Putteti, with abundant pyroxenite bands, have formed at shallow levels of the continental crust.

Table 2: Geobarometry and calculated depth of formation of putteti syenites using amphiboles

Sample	Al ^{Total}	Calculated pressures			
		Pressure P1*	Pressure P2**	Pressure P3 [#]	Pressure P4 ^{##}
1	1.47	3.47	3.53	2.76	3.98
2	1.464	3.44	3.50	2.73	3.96
3	1.50	3.62	3.70	2.88	4.13
4	1.44	3.32	3.36	2.63	3.84
5	1.45	3.37	3.42	2.674	3.89
6	1.473	3.49	3.55	2.77	4.00
7	1.425	3.25	3.27	2.57	3.77
8	1.455	3.40	3.44	2.69	3.91
9	1.441	3.33	3.36	2.63	3.84
10	1.421	3.23	3.26	2.55	3.75
Mean		3.39	3.44	2.69	3.91
Method after					

* Hammarstrom and Zen (1986)	# Johnson and Rutherford (1989)
** Hollister et al. (1987)	## Schmidt (1992)
Depth of crystallisation conversion factor 1 kb = 3.7 km (Tulloch and Challis, 2000)	
Average Depth of Crystallisation is 12.5 Km	

5. Summary and Conclusions

The advanced analytical studies of minerals offer better inferences regarding the P-T conditions that existed during the genesis of the minerals and thus the rocks. The EPMA analysis of amphiboles in the suite, which contains varieties of syenite, pyroxenite and their cumulus counterpart, the hybrid rock, reveals a mean pressure of 3.36Kb and an average depth of crystallization of 12.5Km.

Calcic pyroxenes in Putetti igneous suite of rocks indicate a temperature of formation above 1000°C (Anjana *et al.*, 2019)^[11]. Occurrence of Ca-rich amphiboles in the suite can be attributed to the fractionation of Ca-rich parental magma. Amphiboles might have crystallized at a later stage magmatic fractionation after pyroxenes at a pressure of 3.36Kb. It is very common that igneous bodies are characterized by the co-existence of early crystallizing pyroxenes and late phase amphiboles and such features are noticed worldwide (Percival and Mortensen, 2002)^[20].

6. Conflict of interest

Authors have declared that there is no conflict of interest

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