

Pyroxene Exsolution Textures and P-T Conditions of Anorthosite - Gabbro Rocks of Chimakurthi Pluton, Southeast India

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Abstract

The Chimakurthi Pluton is located on the western margin of the Eastern Ghats Mobile Belt which falls under the Ongole domain of Krishna province from southeastern India. It is an elliptically shaped and concentrically zoned pluton consisting of an olivine clinopyroxenite unit in the centre and olivine gabbronorite unit on the outer margin, with an arcuate shaped anorthosite body towards the northwestern part of the pluton. The anorthosite and olivine gabbronorite consists of variable amounts of cumulus and inter-cumulus phases of plagioclase, olivine, clinopyroxene, orthopyroxene, ilmenite, and magnetite assemblages, respectively. The rocks units registered several igneous and some deformational textures. Electron Probe Micro Analysis was performed to assess the chemical composition of clinopyroxene host ($\text{En}_{44.2-36.1} \text{Fs}_{17.0-12.3} \text{Wo}_{46.5-43.3}$), orthopyroxene lamellae ($\text{En}_{75.9-66.0} \text{Fs}_{30.7-23.0} \text{Wo}_{3.1-0.9}$), olivine ($\text{Fo}_{81.0-72.0}$) and plagioclase ($\text{An}_{74.0-56.0}$) from anorthosite, and clinopyroxene host ($\text{En}_{42.2-38.8} \text{Fs}_{18.9-14.2} \text{Wo}_{46.9-40.2}$), orthopyroxene lamellae ($\text{En}_{71.5-59.0} \text{Fs}_{40.0-25.0} \text{Wo}_{3.3-0.5}$), olivine ($\text{Fo}_{73.0-60.0}$) and plagioclase ($\text{An}_{81.0-72.0}$) from olivine gabbronorite, respectively. The K_D values of the exsolved pyroxenes of all samples range from 0.53 to 1.85, consistent with igneous equilibrium conditions in the pluton. The K_T values range from 0.68 to 1.97, suggesting the influence of post-cumulus solid-state deformation forces following crystallization of the high-temperature primary magma of the pluton. The conversion of pigeonite to orthopyroxene results in considerable amounts of orthopyroxene lamellae growing within the clinopyroxene host and undergoing exsolution due to the sub-solidus re-equilibration during a significant period of slow cooling. The temperature - pressure estimate of exsolved pyroxenes from the present rock units revealed very broad range from 874 to 1226°C and 5 to 14 kbars, respectively. However, the overall pressure increase and temperature decrease from the middle zone anorthosite unit (1101°C, 9.2 kbars) to the outer zone olivine gabbronorite unit (1079°C, 11.2 kbars) suggested the syn-tectonic emplacement of the Chimakurthi pluton into metapelitic country rocks through the Terrane Boundary Shear Zone, associated with the impact of a regional shear-related ductile deformation event (D2) caused by the collision between the juxtaposed Western Dharwar Craton and Eastern Ghats Mobile Belt of India during 1450-800 Ma.

Keywords: Anorthosite, Olivine Gabbronorite, Chimakurthi Pluton, Exsolution Textures, P-T Conditions, EGMB, South India.

Introduction

Proterozoic massif-type anorthosites are composed of leuconorite, leucogabbro, and leucotroctolite (Xu and Morse, 1993). They are commonly associated with high-grade metamorphic terranes (Maji *et al.*, 2010). Mineralogy, petrology and geochemical studies on mafic (Nageswara Rao *et al.*, 2008; Hanumanthu *et al.*, 2008) and massif-type anorthositic rocks formed during the Proterozoic era have been reported from all continents (Ashwal, 1993; Seifert *et al.*, 2010; Anoop *et al.*, 2012; Debeleena Sarkar *et al.*, 2024). Deformational forces have played an important role in modifying the original structure and forms of various types of bodies, such as lensoid, dome, and diaper types (Martignole and Schrijver, 1970; Nagaraju and Chetty, 2005; Nagaraju *et al.*, 2008).

Massif-type anorthosites are characterized by preservation of

magmatic features such as ophitic and sub-ophitic textures, cumulus and inter-cumulus phases, pyroxene and ilmenite exsolution, and zoned textures (Leelanandam, 1997; Ashwal and Wooden, 1989; Rao *et al.*, 1998; Dharma Rao *et al.*, 2004; Joshi *et al.*, 2006; Song *et al.*, 2009; Bhattacharjee *et al.*, 2012). The exsolution textures including other igneous textures are very common in the massif anorthositic rocks of Chimakurthi Pluton (CP) in the Eastern Ghats Mobile Belt (EGMB), India. CP is a Proterozoic massif-type anorthosite body, mafic to ultramafic range in composition and lacking of layers. It is composed of a lithology of olivine gabbronorite, anorthosite, and olivine clinopyroxenite units.

Exsolution textures are crucial in understanding their cooling and decompression histories and in estimating the original high temperatures and pressures at which the host minerals first crystallized (Song *et al.*, 2009). Pyroxenes are one of the best-known multi-component systems in mineralogy (Lindsley, 1983), and the result of unmixing in Ca-Mg-Fe pyroxenes is commonly seen as sets of thin exsolution lamellae (Champness and Copley, 1976; Robinson *et al.*, 1977). Pyroxene phenocrysts exhibit a variety of exsolution features, which have long been reported by

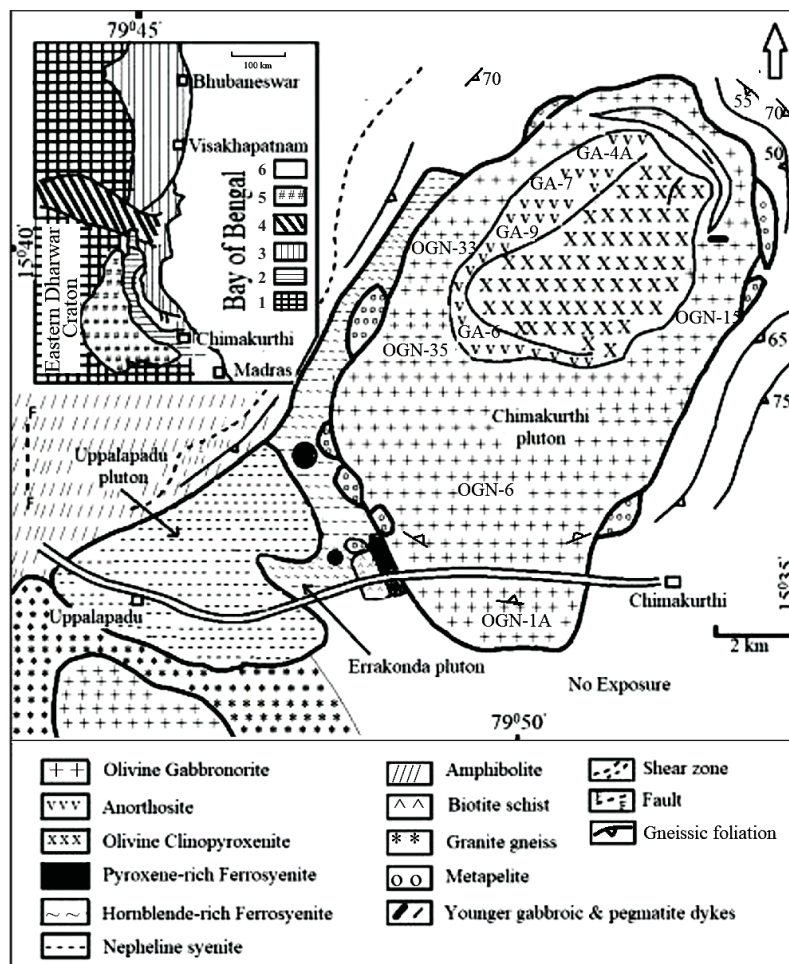


Fig. 1. Geological map of Chimakurthi pluton, Andhra Pradesh, southeast India (Modified after Prasada Rao et al, 1987 and Krishna Reddy *et al.*, 1998). Index map: 1. Archaean craton, 2. Nellore Schist Belt, 3. Eastern Ghats Mobile Belt, 4. Godavari Rift sediments, 5. Cuddapah formations, 6. Alluvium. The map showing location of samples collected for mineral Analyses.

petrologists as composite lamellae of plagioclase and ilmenite with additional lamellae of orthopyroxene or clinopyroxene (Bohlen and Essene, 1978; Dymek and Gromet, 1984; Owens and Dymek, 1995; Rajesh *et al.*, 1998, Rajesh 2006; Rao *et al.*, 2004). Druppel *et al.* (2021) have been studied on the chemical composition of garnet and orthopyroxene and their textural relationships indicate sub-solidus re-equilibration of $790 \pm 80^\circ\text{C}$ and 8 ± 1 kbars conditions from leucotroctolite. The formation of thick lenses of Fe-Ti oxides in the Fe-rich gabbro and ilmenite exsolution lamellae within the titanomagnetite during progressive cooling from 1000 to 800°C and 8 kbars (Mohamed *et al.*, 2024). Pyroxene exsolution textures are petrologically important, where they can show the effects of regional metamorphism and their igneous history imprinted in them (Ollila *et al.*, 1988; Rao *et al.*, 1998; Maji *et al.*, 2010).

The anorthosite and olivine gabbronorites in the present study consist of coarser and finer exsolution lamellae of orthopyroxene in a clinopyroxene host. The objectives of this paper are to discuss the chemical characteristics, pressure-temperature estimates of the exsolved pyroxenes, and emplacement conditions of the CP.

Geology of the Study Area

The CP in southeastern India is an elliptical and concentrically zoned pluton, 15 km long and 6-7 km wide, covering

an area of about 95 km^2 . It is included in the Survey of India Topo Sheet No. 57 M/14, which is bounded on the Survey of India map by coordinates $15^\circ 34'$ to $15^\circ 43'$ N and $79^\circ 48'$ to $79^\circ 55'$ E. (Fig. 1). CP consists of a subordinate olivine clinopyroxenite unit (~18%) in the center and a dominant olivine gabbronorite unit (~70%) on the outer margin, with a small arcuate-shaped anorthosite body (12%) towards the northwestern part of the zoned pluton. It also hosts post-plutonic dykes such as younger gabbro, dolerite, and pegmatite.

The rock units are exposed on undulating hills, where they have been extensively excavated, mostly confined to ground-level exposures in fields and road cuts. There is a decrease in grain size from the center to the margin of the pluton. The peripheral olivine gabbronorite, especially the southwestern margin, shows magmatic layers with a moderate to steep (70 – 78°) inward dips. In some places, the marginal rocks exhibit strain effects, including bending of plagioclase crystals. The Terrane Boundary Shear Zone (TBSZ), which represents the western contact of the Eastern Ghat Mobile Belt (EGMB) and is interpreted as an eastward thrust and cryptic suture (Chetty and Murthy, 1994, 1998; Singh and Mishra, 2002).

The CP occupies the southern part of the TBSZ, which is found in the Ongole domain of the Krishna province (Dobmeier and Raith, 2003). The TBSZ hosts several Meso- to Neoproterozoic

alkaline, granitic and mafic intrusive bodies in the form of ellipsoidal and linear plutons along its length (Leelanandam, 1997; Prasada Rao *et al.*, 1988). Similarly, the CP also intrudes into the metapelitic country rock through the TBSZ between the Mesoproterozoic EGMB and the Paleoproterozoic Eastern Dharwar Craton (EDC).

The strike of the gneisses ranges from NE-SW to NW-SE and dips mainly to the east. The available geochronological data for the EGMB show that the extensive granulite metamorphism at ~1000-900 Ma (Shaw *et al.*, 1997; Mezger and Cosca, 1999) is particularly well established in the EGMB. However, 1000 Ma event has not been reported in the Ongole domain, whereas a ~1670 Ma granulite facies metamorphism event has been reported in this domain (Dobmeier and Raith, 2003). Two major deformation events in the Ongole domain are inferred based on regional granulite facies metamorphism (D1), which is characterized by the development of NE-SW trending foliations parallel to the margin (Fig. 1) with moderate to steep dips at ~1670 Ma (Dobmeier and Raith, 2003), and the development of shear zones (D2) associated with east dipping mylonites and the immediate margins of plutons at several locations in the Ongole domain (Nagaraju and Chetty, 2005) during the period of 1450 - 800 Ma (Shaw and Arima, 1996; Sarkar and Paul, 1998). The age of mafic magmatism reported in this domain ranges from ~1300 to 1000 Ma (Sarkar and Paul, 1998).

Methodology

The chemical composition of orthopyroxene lamellae in clinopyroxene host was determined on a CAMECA SX100 Electron Probe Micro Analyzer (EPMA) at the Petrology Division, Geological Survey of India, Southern Region, Hyderabad. Representative samples from four anorthosite and five olivine gabbro units were selected for mineral analyses. The samples were prepared as uncoated thin sections of 4.5 X 2.5 cm in size and mounted in epoxy. EPMA analysis was carried out at an accelerating voltage of 15 KV. The beam diameter was two microns, the beam current was 20 nA, the beam size was 1 µm, and the counting time was 10 seconds for all analyses. Natural standards such as diopside (Si, Ca, Mg), kyanite (Al), olivine (Mg), almandine (Fe), rhodonite (Mn), albite (Na), orthoclase (K), and a synthetic standard of rutile (Ti) were used for the respective major elemental analyses from various minerals. The use of a scanning electron microscope (SEM) provided advantages in that an image allowed for more precise positioning of the electron beam. To obtain the average composition of the lamellae and host pyroxene, two to four spot analyses were performed from a single grain.

The temperature and pressure conditions of formation of the present rock units are estimated using thermobarometers by Nickel *et al.* (1985), Sen and Jones (1989), Wood and Banoo (1973), Wells (1977) and Putrica (2008).

Results and Discussion

Petrography

The anorthosite and olivine gabbro units are generally gray to grayish black in color. The olivine gabbro is characterized by medium to fine grained and magmatic features such as hypidiomorphic, cumulate, and inter-cumulate, and sub-ophitic textures (Fig. 2a), with labradorite, diopside, hypersthene,

and forsterite as the essential minerals. Spinel, ilmenite, and magnetite are accessory, and hornblende and biotite as the secondary minerals. The plagioclase grains are subhedral and show lamellar and polysynthetic twinning, which are deformed (Fig. 2b). Bent twin lamellae, tapered twins, and slip planes in plagioclase and pyroxene phenocrysts are more commonly present in the constituent rocks of the pluton.

Anorthosite is medium to coarse-grained, hypidiomorphic, hard, and compact in nature. Anorthosite consists of plagioclase, clinopyroxene, olivine, orthopyroxene, and clinopyroxene, olivine, ilmenite, and magnetite are cumulus and inter-cumulus phases respectively (Fig. 2b). Triple junctions can be found in the subhedral plagioclase crystals of anorthosite. Larger clinopyroxene crystals (porphyroblasts) of anorthosite show re-crystallization around their grain boundaries, forming neoblasts, which indicate solid-state deformation. Clinopyroxene phenocrysts range in size from 1.4 to 2.5 cm in both anorthosite and olivine gabbro. Greenish-yellow hornblende is not uncommon, but locally occurs at the grain boundaries of clinopyroxene phenocrysts, while reddish-brown biotite is very rare (Fig. 2c). Both minerals represent post-cumulus alteration of clinopyroxene.

Pyroxene Exsolution Textures

In many basic plutonic rocks, especially those in tholeiitic associations, Ca-rich clinopyroxene intergrown in the orthopyroxene and inverted pigeonite host along the crystallographic orientations of (100) and (001), respectively (Poldervart and Hess, 1951). Robinson (1980) pointed out that clinopyroxene lamellae in the orthopyroxene host and conversely along the (100) and (001) planes are common in metamorphic pyroxenes. Dasgupta *et al.* (1991) reported the thermobarometry of mafic granulites from EGMB indicates exsolution of pigeonite at ~950°C of (100), clinopyroxene in orthopyroxene and vice versa at 750-820°C and formation of garnet at 700-725°C and 7 kbars conditions. Rao *et al.* (2004) reported two sets of coarse and narrow lamellae of clinopyroxene in the orthopyroxene host along the (001) and (100) orientations from the basic igneous complex of the Nellore Schist Belt (NSB). Lamellar and clot like ilmenite exsolution textures in titanomagnetite, revealed that they result from multiple mechanisms like: oxy exsolution due to oxidation; sub-solidus re-equilibration between ilmenite and magnetite involving elemental diffusion of Fe, Ti, Cr, Co, Ni; exsolution related to lattice defects caused by rapid cooling (Wang *et al.*, 2025).

The anorthosite and olivine gabbro of CP has found significant amounts of coarser and finer exsolution lamellae of orthopyroxene in the clinopyroxene host along the crystallographic orientation of (001). However, pyroxene exsolution textures are not observed in the olivine clinopyroxene unit. The width of the coarser and finer lamellae ranges from 0.01-0.025 mm and 0.002-0.001 mm, respectively. The finer lamellae exhibit minute spacing between them (Fig. 2c). The coarser orthopyroxene lamellae shows more and irregular spacing and, often, see slip planes in the lamellae (Fig. 2d). Thin lamellae rarely grow between the coarse lamellae (Fig. 2d). The total volume proportion of orthopyroxene lamellae is estimated to be ~15%. Small amount of ilmenite is also found as very thin exsolution rods, rodlets, platelets, clots, blebs like exsolution in the crystallographic orientation (100) of the clinopyroxene host (Fig. 2c). The association of ilmenite exsolution in clinopyroxene phenocrysts suggests that oxidizing

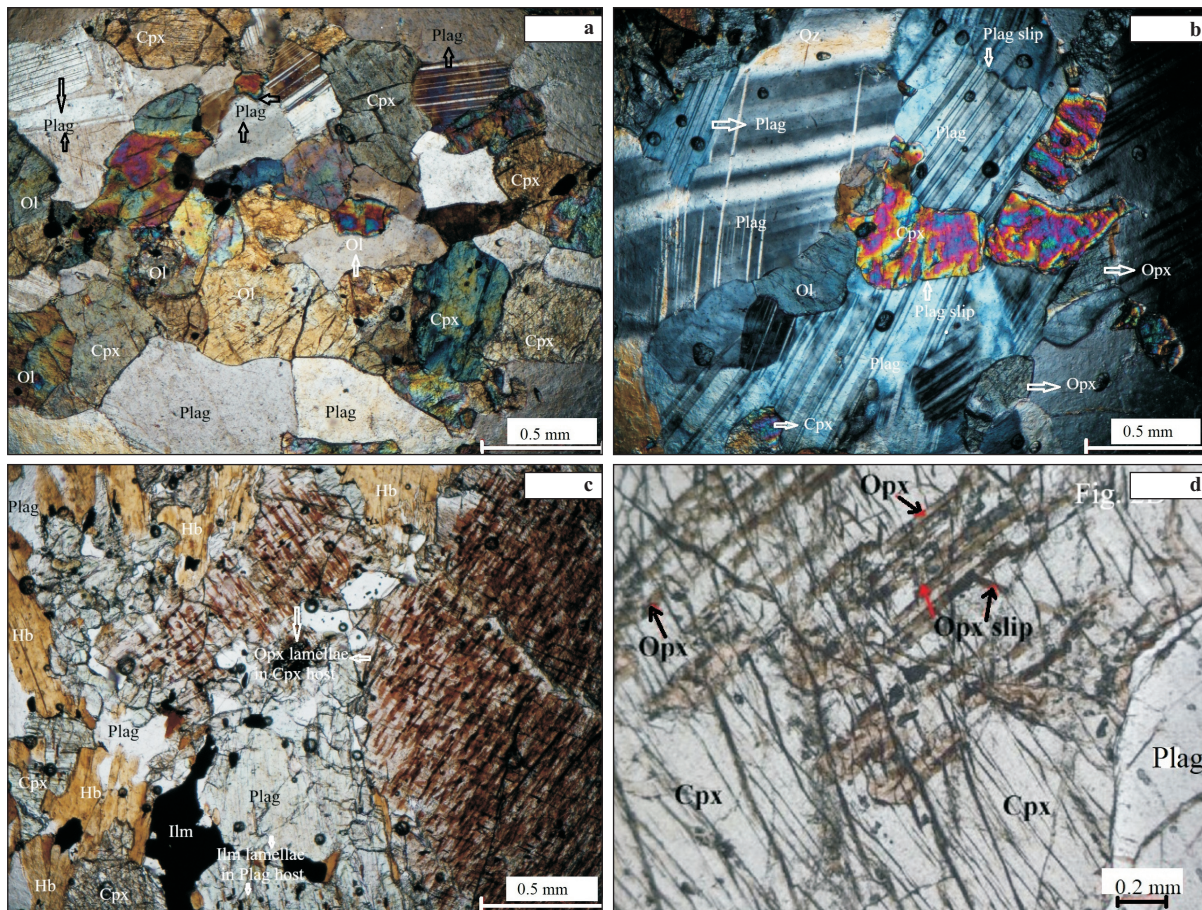


Fig.2. a. Photomicrograph of olivine gabbronorite showing the cumulus texture of olivine (Ol), clinopyroxene (Cpx), orthopyroxene (Opx) and plagioclase (Plag) grains (XPL). **b.** Photomicrograph of anorthosite showing typical megacrystic plagioclase (Plag) with different sets lamellar and polysynthetic twinning and bent lamellae, and also observed the fracturing and slip planes as pointed by arrowheads. Note that the inter-cumulus phases of clinopyroxene (Cpx) and orthopyroxene (Opx) in between Plag laths (XPL). **c.** Photomicrograph of olivine gabbronorite showing finer exsolution lamellae of orthopyroxene (Opx) in the clinopyroxene (Cpx) host along the (001) crystallographic orientation. Minute spacing is observed between finer lamellae. Note the very finer, needle, rods, clots and blebs like ilmenite (Ilm) exsolution along the (100) crystallographic directions of Cpx and Plag. Hornblende (Hb) development at the boundary of Cpx phenocrysts are noticeable (XPL). **d.** Photomicrograph of anorthosite showing coarser exsolution lamellae of orthopyroxene (Opx) in the clinopyroxene (Cpx) host parallel to (001) crystallographic orientation. Note the more spacing between two coarser lamellae and arrowhead indicates slip planes in the orthopyroxene (Opx) lamellae (XPL).

conditions played an important role in controlling the properties and composition of the phenocrysts (Rajesh *et al.*, 1998).

Chemical Characteristics

The ortho- and clinopyroxene analyses of olivine gabbronorite and anorthosite of CP are presented in table 1 and 2.

Figure 3a shows the Mg-rich forsterite composition, which varies from $\text{Fo}_{81.0-72.0}$ and $\text{Fo}_{73.0-60.0}$ in anorthosite and olivine gabbronorite, respectively. The plagioclase composition is Ca-rich, varying continuously from labradorite to bytownite, with an interval between An_{74} to An_{56} in anorthosite and An_{81} to An_{72} in olivine gabbronorite (Fig. 3b). Olivine gabbronorite has a higher An content than anorthosite, indicating the comparatively high-pressure conditions that existed during the cooling of olivine gabbronorite.

The chemical data for both clinopyroxene and orthopyroxene are plotted in the pyroxene quadrangle (Fig. 3c), clearly showing that the compositional range of anorthosite for the clinopyroxene host is ($\text{En}_{44.2-36.1}$ $\text{Fs}_{17.0-12.3}$ $\text{Wo}_{46.5-43.3}$), orthopyroxene lamellae ($\text{En}_{75.9-66.0}$ $\text{Fs}_{30.7-23.0}$ $\text{Wo}_{3.1-0.9}$), olivine ($\text{Fo}_{81.0-72.0}$) and plagioclase ($\text{An}_{74.0-56.0}$). Similarly, the olivine gabbronorite has a compositional range of

clinopyroxene host ($\text{En}_{42.2-38.8}$ $\text{Fs}_{18.9-14.2}$ $\text{Wo}_{46.9-40.2}$), orthopyroxene lamellae ($\text{En}_{71.5-59.0}$ $\text{Fs}_{40.0-25.0}$ $\text{Wo}_{3.3-0.5}$), olivine ($\text{Fo}_{73.0-60.0}$) and plagioclase ($\text{An}_{81.0-72.0}$). Figure 3c shows that the clinopyroxene cluster is closer to diopside than to salite, while the orthopyroxene cluster shows a composition of bronzite and hypersthene. Clinopyroxene has a high Al_2O_3 concentration of up to 5.13 wt. %, while orthopyroxene lamellae also contain a high amount of Al_2O_3 , up to 3.80 wt. %. Therefore, the clinopyroxene concentration always has a higher Al_2O_3 concentration than orthopyroxene.

The values of Ti, Cr, and Na (0.004-0.019, 0, 0.026-0.057, respectively) vs. Al_2O_3 (0.036-0.229) plot (Fig. 4) suggest that the pyroxenes are of magmatic origin (Berger *et al.*, 2005). Therefore, the chemical trend of decreasing Fs content and enrichment of Wo and En components, very low Ti (<0.02 a.p.f.u), and high value of Mg# (>60) suggest that the clinopyroxene of the present study is derived from a tholeiitic basaltic magma source rich in Mg-Al. The Mg# of the clinopyroxene (66.60-77.78 = mean; 71.27%), which is less than 86% is further suggested by the report of Le Bass (1962) and Carmichael (1967) that crystal fractionation and gravitational settling processes were involved during the cooling of the rocks of the present study.

Table 1: EPMA data (Wt.%) of exsolved pyroxenes from representative samples of Anorthosite of Chimakurthi pluton, Southeast India

Sample No.	GA-6(3) [#]		GA-9(4) [#]		GA-7(2) [#]		ANG-4A(4) [#]	
	Cpx H	Opx L	Cpx H	Opx L	Cpx H	Opx L	Cpx H	Opx L
SiO ₂	50.80	49.62	49.48	52.99	50.42	49.62	50.52	51.50
Al ₂ O ₃	3.17	1.89	4.28	2.73	3.29	1.59	3.99	2.28
TiO ₂	0.41	0.29	0.89	0.27	0.46	0.09	0.41	0.28
FeO*	10.32	16.38	7.52	13.60	10.38	6.38	8.71	20.01
MgO	12.44	29.71	14.8	25.81	12.30	29.71	14.16	24.10
MnO	0.41	0.35	0.17	0.31	0.51	0.35	0.19	0.40
CaO	22.01	1.24	20.06	1.74	21.83	0.54	20.63	1.61
Na ₂ O	0.39	0.04	0.48	0.02	0.30	0.04	0.45	0.41
K ₂ O	0.01	0.02	0.01	0.00	0.48	0.02	0.01	0.02
P ₂ O ₅	0.00	0.10	0.03	0.00	0.02	0.01	0.00	0.01
Cr ₂ O ₃	0.11	0.12	0.25	0.15	0.11	0.10	0.06	0.01
ZnO	0.00	0.00	0.05	0.00	0.01	0.00	0.00	0.00
ZrO ₂	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Total	100.07	99.70	98.91	97.70	99.79	99.48	98.96	100.92
Number of ions calculated on the basis of 6 oxygen								
Si	1.9141	1.8285	1.875	0.9282	1.9043	1.8479	1.8945	1.9004
AlIV	0.0859	0.1715	0.124	0.7180	0.0857	0.0110	0.1054	0.0996
AlVI	0.0549	0.000	0.066	0.0453	0.0517	0.500	0.0712	0.0000
Ti	0.0116	0.0080	0.025	0.0074	0.0131	0.0250	0.0116	0.0078
Fe*	0.3252	0.5048	0.232	0.5076	0.3279	0.5010	0.2737	0.6175
Mg	0.6988	1.6321	0.830	1.4001	0.6869	1.6494	0.7932	1.3257
Mn	0.0099	0.0109	0.005	0.0096	0.0163	0.0110	0.0066	0.0125
Ca	0.8886	0.0490	0.814	0.0289	0.8834	0.0215	0.8306	0.0637
Na	0.0265	0.0029	0.035	0.0014	0.0293	0.0029	0.0328	0.0293
K	0.0001	0.0009	0.001	0.0000	0.0231	0.0010	0.0005	0.0009
P	0.0000	0.0000	0.001	0.0000	0.0000	0.0000	0.0000	0.0010
Cr	0.0000	0.0035	0.007	0.0043	0.0003	0.0033	0.0018	0.0000
End Members								
Wo %	46.4	2.24	43.33	1.59	46.50	0.99	43.77	3.17
En %	36.5	74.66	44.28	72.21	36.10	75.94	41.80	66.05
Fs %	17.1	23.10	12.39	26.20	17.20	23.06	14.42	30.76
Mg*	67.23	62.56	77.78	76.64	66.60	75.99	73.88	66.07
KD		1.66		1.31		0.83		1.20
KP		0.99		0.68		0.99		1.28

* Sample numbers; GA-6: Gabbroic anorthosite; GA-7: Gabbroic anorthosite; GA-9: Gabbroic anorthosite; ANG-4A: Anorthositic Gabbro. ** Total Iron expressed as FeO; Mg# = 100Mg/(Mg+Fe¹+Mn); Wollastonite (Wo) = 100 x Ca/(Mg+Fe²+Ca); Ferrosilite (Fs) = 100 x Fe²/Mg+Fe²+Ca; Enstatite (En) = 100 x Mg/(Mg+Fe²+Ca); $KD = (X_{Mg}^{OPX} / 1 - X_{Mg}^{CPX}) \times (1 - X_{Mg}^{CPX} / X_{Mg}^{CPX})$ ----- (Kretz, 1963); $KP = [(Fe^{2+}/Mg) Ca-poor / Fe^{2+}/Mg) Ca-rich]$ ----- (Bartholome, 1962); # - Average of multiplespot analyses from Single grain; Cpx H- Clinopyroxene Host; Opx L- Orthopyroxene Lamellae

Distribution and Partition Coefficients

The values of the distribution coefficient (K_D) and partition coefficient (K_P) of the pyroxenes from the present study are presented in Table 1-2. The estimated K_D values for anorthosite range from 0.83 to 1.66, while olivine gabbroanorthites yield 0.53 to 1.85, respectively. The K_D values for both types of rocks are within

the Kretz (1963) igneous range. The K_D values indicate the high temperatures consistent with igneous equilibration conditions prevailed in the formation of pyroxene exsolution textures at deep crustal levels.

According to Bartholome (1962), the K_P values of four anorthosite (GA-6, GA-7, GA-9, ANG-4A) and two olivine gabbroanorthite samples (OGN-1A, OGN-15) range from 0.68 to 1.31,

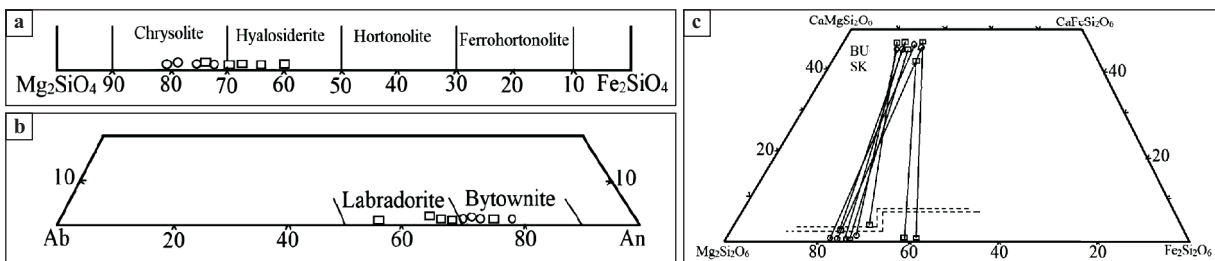


Fig.3. a. Fo-Fa join plot showing the composition of olivine. **b.** Ab-An join plot showing composition of plagioclase feldspars. **c.** Pyroxene quadrilateral showing the composition of clinopyroxenes and orthopyroxenes.

Table 2: EPMA data (Wt.%) of exsolved pyroxenes from representative samples of olivine gabbroanorthites of Chimakurthi pluton, Southeast India

Sample No.	OGN 1A (3) ³		OGN-6 (2) [#]		OGN-15A (2) [#]		OGN-33 (3) [#]		OGN-35 (2) [#]	
	Cpx H	Opx L	Cpx H	Opx L	Cpx H	Opx L	Cpx H	Opx L	Cpx H	Opx L
SiO ₂	49.42	52.89	52.27	52.70	51.82	52.19	51.04	52.01	51.06	52.49
Al ₂ O ₃	5.13	3.80	1.93	3.35	2.02	1.03	3.62	1.05	3.19	1.20
TiO ₂	0.67	0.30	0.19	0.28	0.17	0.04	0.62	0.06	0.64	0.04
FeO*	11.44	16.61	8.67	16.14	8.82	21.13	7.73	21.31	8.63	24.72
MgO	12.87	24.98	13.21	25.19	13.26	24.88	14.26	24.52	14.20	20.59
MnO	0.14	0.10	0.22	0.26	0.20	0.42	0.16	0.39	0.18	0.48
CaO	17.67	0.87	22.21	1.65	21.71	0.39	20.64	0.41	20.25	1.39
Na ₂ O	0.78	0.14	0.44	0.02	0.48	0.01	0.60	0.01	0.52	0.03
K ₂ O	0.31	0.00	0.00	0.00	0.00	0.01	0.03	0.03	0.00	0.1
P ₂ O ₅	0.01	0.03	0.02	0.00	0.00	0.02	0.00	0.00	0.00	0.03
Cr ₂ O ₃	0.03	0.17	0.03	0.15	0.02	0.00	0.07	0.05	0.08	0.00
ZnO	0.06	0.01	0.03	0.09	0.00	0.00	0.00	0.00	0.08	0.04
ZrO ₂	0.03	0.00	0.00	0.00	0.01	0.13	0.09	0.03	0.00	0.05
Total	98.56	99.54	99.22	99.83	98.51	100.1	98.86	100.0	98.83	101.0
No. of ions calculated on the basis of 6 oxygens										
Si	1.8800	1.9132	1.9646	1.9166	1.9613	1.9352	1.9139	1.9322	1.9201	1.9627
AlIV	0.1190	0.0818	0.0540	0.0834	0.0387	0.0642	0.0865	0.0678	0.0795	0.0373
AlVI	0.1100	0.0306	0.0499	0.0602	0.514	0.0000	0.0731	0.0000	0.0614	0.0156
Ti	0.0190	0.0082	0.0051	0.0077	0.0048	0.0004	0.0175	0.0621	0.0181	0.0011
Fe*	0.3400	0.5038	0.2723	0.4909	0.2792	0.6552	0.2424	1.1230	0.2714	0.7730
Mg	0.7290	1.3506	0.7399	1.3657	0.7402	1.3753	0.7947	1.3580	0.7960	1.1477
Mn	0.0040	0.0040	0.0070	0.0080	0.0031	0.0132	0.0052	0.0155	0.0057	0.0152
Ca	0.7290	0.0338	0.8944	0.0645	0.8804	0.0142	0.8292	0.0295	0.8159	0.0557
Na	0.0570	0.0098	0.0316	0.1014	0.0316	0.0015	0.0436	0.0005	0.0379	0.0022
K	0.0150	0.0005	0.0000	0.0000	0.0000	0.0000	0.0014	0.0003	0.0000	0.0005
P	0.0000	0.0000	0.0004	0.0000	0.0004	0.0006	0.0000	0.0000	0.0000	0.0008
Cr	0.0000	0.0049	0.0004	0.0043	0.0004	0.0000	0.0009	0.0000	0.0024	0.0000
End Members										
Wo %	40.20	1.79	46.91	3.30	46.14	0.72	43.70	3.17	43.35	0.57
En %	40.77	71.52	38.81	71.20	39.21	59.06	41.80	66.05	42.22	59.41
Fs %	18.97	26.69	14.28	25.50	14.65	39.97	14.50	30.78	14.43	40.02
Mg*	67.93	72.70	72.59	73.24	67.39	59.36	73.88	66.07	74.17	59.28
KD	1.85		0.80		0.74		1.82		1.83	
KP	1.27		1.02		1.77		0.53		1.97	

* Sample numbers; GA-6: Gabbroic anorthosite; GA-7: Gabbroic anorthosite; GA-9: Gabbroic anorthosite; ANG-4A: Anorthositic Gabbro. ** Total Iron expressed as FeO; Mg# = 100Mg/(Mg+Fe²⁺+Mn); Wollastonite (Wo) = 100 x Ca/(Mg+Fe²⁺+Ca); Ferrosilite (Fs) = 100 x Fe²⁺/Mg+Fe²⁺+Ca; Enstatite (En) = 100 x Mg/(Mg+Fe²⁺+Ca); KD = (X_{Mg}^{OPX} / 1 - X_{Mg}^{CPX}) x (1 - X_{Mg}^{CPX} / X_{Mg}^{CPX}) ----- (Kretz, 1963); KP = [(Fe²⁺/Mg) Ca-poor / Fe²⁺/Mg) Ca-rich] ----- (Bartholme, 1962); # - Average of multiplespot analyses from Single grain; Cpx H- Clinopyroxene Host; Opx L- Orthopyroxene Lamellae

are indicative of igneous range, while the remaining three olivine gabbroanorthite samples (OGN-6, OGN-33, OGN-35) range from 1.77 to 1.97, which are within the Kretz (1963) metamorphic range. The K_p values of the above three olivine gabbroanorthite samples inferred that the CP was heavily influenced by a ductile deformational event (D2), resulting in a metamorphic range of K_p

values and deformational textures. The preservation of curved and tapered twin lamellae and slips along the twin planes of plagioclase laths and slips across pyroxene exsolution lamellae also supports the effect of solid-state ductile deformation on the pluton.

Temperatures and Pressures of Crystallization

High-temperature (~1000°C) pigeonite exsolution lamellae in a host augite from the Bushveld Complex of South Africa were described by Robinson *et al.* (1977). The crystallization temperature of igneous pyroxenes for Adirondack metamorphosed gabbroic anorthosite and gabbro was reported by Bohlen and Essene (1978) to be 1150°C and 1100°C, respectively. The composition of exsolved and granular pyroxenes of anorthosite and syenite from the High Peak areas of the Adirondack and Labrador suggests a trend of igneous crystallization at pressures greater than or equal to 9 kbars (Ollila *et al.*, 1988). Coarser exsolution of orthopyroxene in sub-calcic augite has been reported in mafic granulites from the Groove Mountains, which recorded a pre-metamorphic temperature at 970°C, a metamorphic temperature at 850°C, and an exsolution temperature at 740-770°C (Liu *et al.*, 2003).

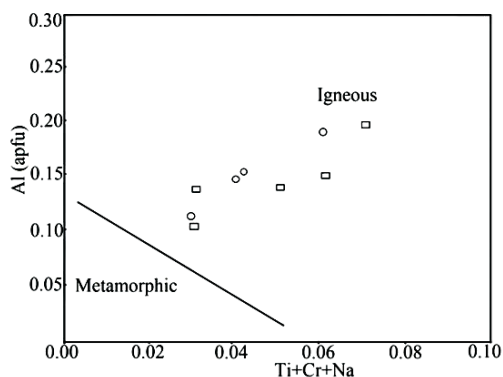


Fig. 4. Ti+Cr+Na vs. Al (alfu) variation diagram for the rock units of present study

Table 3: Temperature and Pressure estimate for the anorthosites and olivine gabbroites from Chimakurthi pluton, Southeast India

Method	Anorthosites				Olivine Gabbroites				
	GA-6	GA-9	GA-7	ANG- 4A	OGN-1A	OGN-6	OGN-15A	OGN-33	OGN-35
Nickel <i>et al.</i> (1985)	1005	1128	1000	1112	1185	1002	1063	1093	1132
Sen and Jones, (1989)	1116	1011	945	1213	1074	1214	1000	885	1178
Wood and Banoo (1977)	1150	1164	1190	1112	1074	1111	1084	1095	1070
Wells (1977)	1159	1218	1129	1214	1148	1189	1179	1203	1226
Putrica (2008)	940	1198	918	1109	1104	896	874	922	974
Pressure (kbars)	12	9	5	11	14	10	11	8	13

The description of samples is as shown in Table 1-2; Pressures estimated as per Putrica (2008)

Clinopyroxene and orthopyroxene from the Perinthatta anorthositic gabbro of southwest India exhibit exsolution intergrowths of pyroxenes and Fe–Ti oxides, suggesting that subcalcic augite and pigeonite equilibrated at ~935°C, with different lamellar generations forming between ~914 and ~748 °C (Rajesh, 2006).

Table 3 presents temperature and pressure estimates based on different two-pyroxene thermobarometers for exsolved pyroxenes from the anorthosite recorded the temperature and pressure range of 918 to 1218°C and 5 to 12 kbars, and the olivine gabbroite ranged from 874 to 1226°C and 8 to 14 kbars, respectively. However, the temperature values obtained using the thermometers of Wood and Banoo (1973), Wells (1977) and Nickel *et al.* (1985) are practically the same for all samples (>1000°C). The reason for the formation of temperatures above 1000°C is that pigeonite inverts into orthopyroxene and undergoes exsolution due to a sub-solidus re-equilibrium condition during a significant period of slow cooling.

The pyroxene compositions are consistent with an igneous origin, as evidenced by the sub-ophitic texture of plagioclase, olivine, clinopyroxene, and orthopyroxene, and triple junctions in the subhedral plagioclase crystals, cumulus and inter-cumulus phases. (Fig. 2a-b). Orthopyroxene lamellae grown as a result of decreased solubility in the clinopyroxene host during slow cooling, as supported by Chalokwu and Grant (1990). Although no pervasive granulite facies metamorphism has been reported in the CP region since 1000–900 Ma (Mezger and Cosca, 1999), textures such as undulatory extinction, bent lamellae, and slip planes in plagioclase laths, as well as orthopyroxene lamellae, and also granular texture around the clinopyroxene phenocrysts, suggest post-cumulus solid-state D2 deformation forces activity on the western margin of the CP during cooling.

The mineral foliations that are parallel to the margins of the CP as well as with orientation of TBSZ (Fig. 1), provided the evidence that the pluton attained an elliptical shape during emplacement in relation to a regional shear-related ductile D2 deformation event. The overall decrease in mean temperature and increase in pressure (Table 3) between the anorthosite unit (1101°C; 9.2 kbars) and the outer margin olivine gabbroite unit (1079°C; 11.2 kbar) support diapiric ascent of the CP from lower to middle crustal levels under the above said conditions. The abundant clinopyroxene accumulation in the olivine gabbroite (81-72) and anorthosite (74-56) indicate moderate to high-pressure conditions during the cooling of pluton.

The ascent of the CP is syn-tectonic under moderate to high pressures at great depth through the TBSZ, probably during the period of gabbroic magmatism (~1300-1000 Ma) in the Ongole domain of the EGMB (Sarkar and Paul, 1998). The syn-tectonic emplacement of the CP is associated with a regional shear-related deformation event (D2) caused by the collision between the

juxtaposed WDC and EGMB between 1450-800 Ma (Sarkar and Paul, 1998; Shah and Arima, 1996; Saha, 2004), which is also supported by the field and structural data of the Pasugallu gabbro pluton, located 38 km north of the CP on the western margin of the EGGT in India (Nagaraju and Chetty, 2005). Dasgupta *et al.* (1997) reported retrograde mineral assemblage in the metapelites at 750 to 1000°C and 6 kbars due to thermal metamorphic effect at the contact of CP and surrounding metapelitic country at mid crustal level, confirms the CP is intruded gradually from lower crust beyond 1000°C.

Based on the tectonic setting, thermo-barometry and zoned textures, the Chimakurthi massif anorthosite body is considered to be a gradually intruded pluton from the great depth and high temperature condition. The gabbroic magmatism in the Ongole domain of EGMB during 1300-800 Ma was synchronous with the amalgamation and breakup of the supercontinent Rodinia, as the numerous mafic counter-parts are recorded in the world at several orogenic belts, notably the Grenvillian Orogen (Lawlor *et al.*, 1999).

Conclusions

A significant period of slow cooling at moderate to higher pressure conditions in the lower to middle crustal level of the Chimakurthi Pluton has resulted in the formation of several magmatic and few deformatinal textures in the mineral phases of the anorthosite and olivine gabbroite units. Coarser and finer orthopyroxene lamellae in clinopyroxene hosts along the crystallographic orientation of (001) are formed by inversion of pigeonite into orthopyroxene and are subjected to formation exsolution textures due to the sub-solidus re-equilibration conditions that existed during the significant period of slow cooling. The composition of olivine, clinopyroxene host, and orthopyroxene lamellae is very Mg-rich. The composition of plagioclase is anorthite-rich. Chemical composition of the pyroxenes indicates a magmatic origin. The mineral layering, cumulus and inter-cumulus textures, and higher Mg# indicate a process of crystal fractionation and gravitational settling that occurred during the formation of the present rocks. K_D values range from 0.53 to 1.85, and K_P values range from 0.68 to 1.97, supporting an igneous equilibrium state following the influence of post-cumulus ductile deformation forces activity on the rock types of CP. The overall pressure increase and temperature decrease from the middle zone anorthosite unit to the marginal zone olivine gabbroite unit, inferred that the CP is syn-tectonically emplaced into the metapelitic country through the TBSZ, probably during the period of gabbroic magmatism (1300-1000 Ma), associated with the impact of a regional shear related ductile deformation event (D2; 1450-800 Ma) caused by the

collision between the juxtaposed WDC and EGGT. Based on the tectonic setup, thermo-barometry, and magmatic fabric, the Chimakurthi pluton is considered to be a gradual emplacement magmatic body during the period of 1400 to 800 Ma.

Conflict of Interests

The author of this manuscript declares no conflicts of interests.

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