

# A note on the origin of Clinopyroxene megacrysts from the Udiripikonda lamprophyre, Eastern Dharwar Craton, southern India

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## ABSTRACT

Abundant sub-rounded to sub-angular and centimeter-sized clinopyroxene megacrysts constitute a conspicuous feature of the Udiripikonda lamprophyre, located in the Eastern Dharwar craton, Southern India. These clinopyroxene megacrysts, at times, are also associated with minor amounts of biotite. The megacrysts lack reaction-rim or any other disequilibrium textures generally displayed by crustal and mantle xenocrysts/xenoliths entrained in such volatile-rich magmas. Cr<sub>2</sub>O<sub>3</sub>-impoverished (< 0.1 wt%) nature of the clinopyroxene megacrysts preclude them from being chrome-diopside, derived from the disaggregation of upper mantle rocks, and commonly found entrained in kimberlites. The clinopyroxene megacrysts (Wo<sub>47.43-49.20</sub>En<sub>32.44-33.64</sub>Fs<sub>13.73-15.03</sub>Ac<sub>3.32-4.69</sub>) and associated biotite (Mg#: 0.84- 0.90) are compositionally similar to the clinopyroxene (Wo<sub>43.68-47.76</sub>En<sub>37.47-44.58</sub>Fs<sub>8.36-12.31</sub>Ac<sub>2.70-3.38</sub>) and biotite (Mg#: 0.84- 0.88) occurring as liquidus phases within the host lamprophyre. Clinopyroxene barometry reveals an overlapping pressure estimates for megacrysts (9.8 to 12.4 kbar) and phenocrysts (8.4 to 10.1 kbar). Likewise, the Ti-in-biotite geothermometry also suggests an overlapping temperature range of 957°C to 1097°C and 904°C to 1069°C for megacrystal suite and phenocrysts respectively at pressure of ~10 kbar. The clinopyroxene ± biotite megacrysts of this study are, thus, inferred to be cognate products which crystallized under high- to medium-pressure conditions during the evolution of lamprophyre magma.

**Key words:** Clinopyroxene, Megacryst, Lamprophyre, Udiripikonda, Dharwar Craton, Southern India.

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## INTRODUCTION

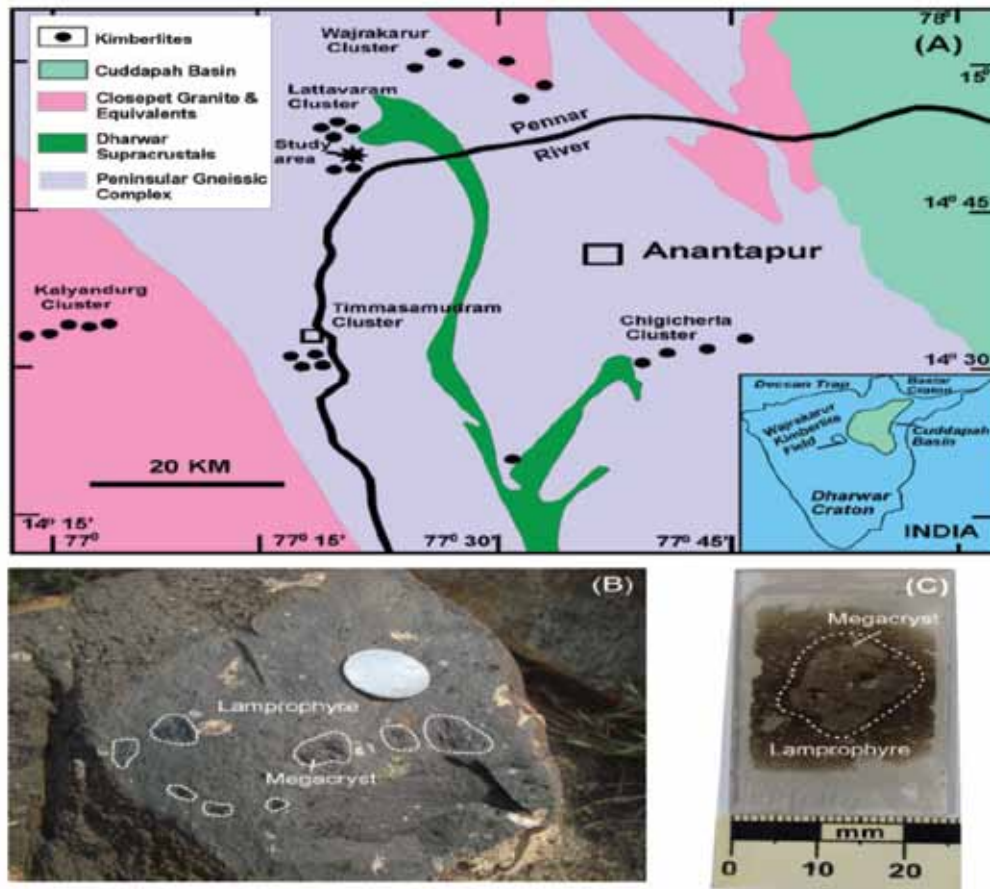
Megacrysts (> 1 cm) of discrete minerals such as clinopyroxene, mica, amphibole, ilmenite etc have been documented from deep-mantle derived rock types such as kimberlites, and alkali-basalts (Dawson and Smith, 1977; Wass, 1979; Boyd et al., 1984; Colville and Novak, 1991); but an understanding of their origin remains unclear. A variety of models- ranging from cognate (Boyd and Nixon, 1978; Schulze, 1987) through xenocrystal (Jones et al., 1987; Davies et al., 2001) to metasomatic (Pivin et al., 2009; Kopylova et al., 2009) and even magma-mixing (Brooks and Printzlau, 1978) have been proposed to account the genesis of these megacrysts. Occurrence of megacrysts in general, and those of clinopyroxene in particular, is rare in lamprophyres but nevertheless has been recorded in the literature (see Brooks and Rucklidge, 1973; Praegel, 1981; Larsen, 1981; Neal and Davidson, 1989; Brodie and Cooper, 1989; Jaques and Perkin, 1994). The purpose of this note is to document the occurrence of rare clinopyroxene megacrysts from a lamprophyre dyke from the Udiripikonda, eastern Dharwar craton, southern India, and to deduce their plausible origin from textural relations, chemical composition and pressure-temperature estimations.

## GEOLOGICAL SETTING

The lamprophyre of this study was reported by the Geological Survey of India (Ravi et al., 1998) and occurs as ~1 km long and 1.2 m wide N70°W trending dyke near the village of Udiripikonda (14°49'33.6"N; 77°19'40.6"E). The Udiripikonda lamprophyre intrudes the granite-gneisses (Peninsular Gneissic Complex) of the Eastern Dharwar Craton, southern India (Figure 1A) is located in the Wajrakarur kimberlite field, where tens of kimberlites confined to distinct clusters ranging in age from Mesoproterozoic (ca. 1090 Ma) to Late Cretaceous (ca. 90 Ma) age were reported (Kumar et al., 2007; Chalapathi Rao et al., 2013, 2016). The lamprophyre is melanocratic and is characterized by crustal xenoliths (felsic material of quartz and feldspar derived from the country granitoids). A number of greenish colored megacrysts (Figure 1B) of clinopyroxene varying in size up to 2 cm are conspicuous and widespread in this dyke.

## PETROGRAPHY

Petrographic studies show that the host lamprophyre has typical panidiomorphic-porphyrific texture dominated by phenocrysts and microphenocrysts of clinopyroxene,



**Figure 1.** (A) Geological map of the Wajrakarur kimberlite field in the eastern Dharwar Craton, southern India, showing various kimberlite clusters (after Nayak and Kudari, 1999) and location of lamprophyre (Udiripikonda) of this study. (B) Outcrop of the Udiripikonda lamprophyre displaying megacrysts (encircled by white dotted patterns). The diameter of the 2 rupee coin shown is 2.4 cm. (C) An overview photograph of the megacryst in a thin section.

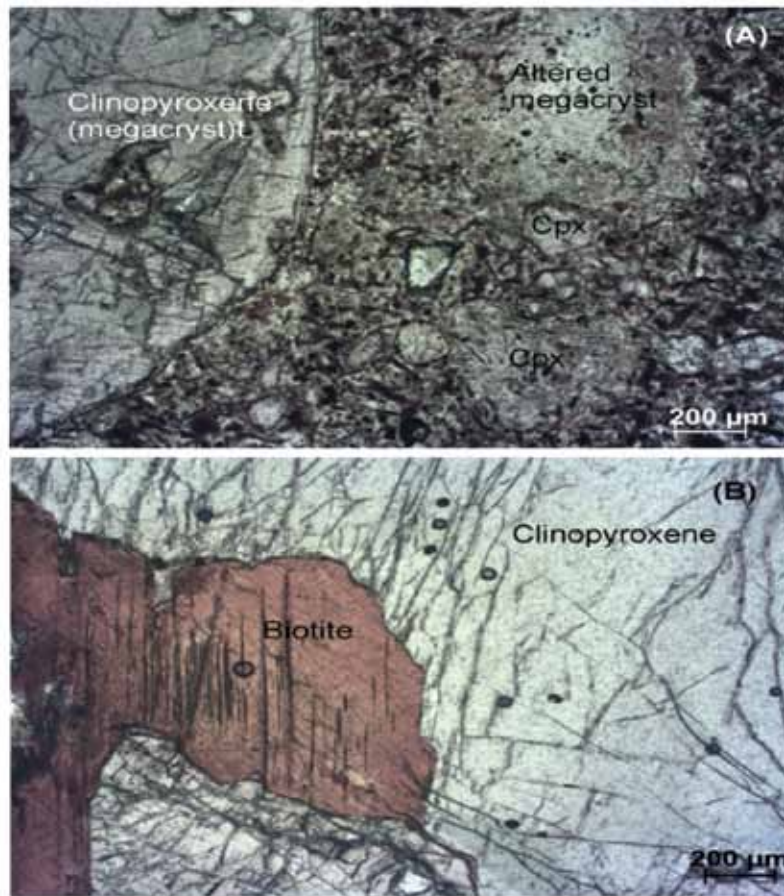
biotite and olivine in a groundmass of feldspar and its bulk-geochemistry classifies it to belong to alkaline lamprophyre variety (cf. Rock, 1991). Detailed petrology and geochemistry of the lamprophyre are beyond the scope of this paper and will be addressed elsewhere. The clinopyroxene megacrysts vary in their shape from sub-rounded to sub-angular, with the former in great majority, and display sharp contacts with the host lamprophyre (Figure 1B and C). Some of the megacrysts are altered but a majority of them are fresh (Figure 2A). None of the studied megacrysts display kelyphitic rims or any other disequilibrium textures displayed commonly by the entrained crustal and mantle xenocrysts/xenoliths in the host magmas. A few of the megacrysts also contain biotite in association with clinopyroxene (Figure 2B) and both of them exclude any effects of deformation.

## RESULTS

Mineral chemistry was determined by a CAMECA-SXFive electron microprobe (EPMA) at the Department

of Geology, Banaras Hindu University, Varanasi, using wavelength-dispersive spectrometry and a LaB<sub>6</sub> filament. An accelerating voltage of 15 kV, a beam current of 10 nA and a beam diameter of 1  $\mu$ m along with TAP, PET and LLIF crystals were employed for major elements. A number of natural and synthetic standards were used for calibration. After repeated analyses it was found that the error on major element concentrations is <1% whereas the error on trace elements varied between 3-5%.

EPMA studies revealed the megacrystic clinopyroxene ( $Wo_{47.43-49.20} En_{32.44-33.64} Fs_{13.73-15.03} Ac_{3.32-4.69}$ ) as well as that present as phenocrysts in the host lamprophyre ( $Wo_{43.68-47.76} En_{37.47-44.58} Fs_{8.36-12.31} Ac_{2.70-3.38}$ ) which are essentially diopsidic in nature (see Table 1; Figure 3A). They are all calcic [ $Ca/(Ca+Mg) > 0.49$ ] and magnesian [ $Mg\#: 0.80-0.90$ ] and display a strong overlap in their composition. All of their  $Cr_2O_3$  contents are essentially <0.1 wt% and exclude the compositional field of chrome-diopside megacrysts, which are considered to be either disaggregated fragments of garnet- and spinel-bearing mantle peridotites or even those megacrysts of cognate origin found in



**Figure 2.** (A) Photomicrographs of the Udiripikonda lamprophyre showing megacrystic and phenocrystic phases of clinopyroxene (cpx) in the host lamprophyre. Note also the presence of an altered megacryst. Plane polarized light; (PP/U1/4). (B) Photomicrograph showing the association of biotite with megacrystic clinopyroxene Plane polarized light; (PP/U1/4).

kimberlites (Figure 3B). The biotite associated with the megacrystic diopside also displays a strong compositional overlap with the phenocrystal biotite in lamprophyre in terms of MgO, FeO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Mg# (0.84 – 0.88) (see Table 2; Figure 4A and B). However, the megacrystic mica is relatively more enriched in TiO<sub>2</sub>, BaO and F contents than those occurring as phenocrysts (Table 2).

### Clinopyroxene Geobarometry

Experimental investigation on high Ca-pyroxenes demonstrate that Ti and Al content in clinopyroxene depends on the temperature of crystallization in the range of 1230°C to 900°C (Gerke et al., 2005). Ti and Al content in clinopyroxene from the megacrystic suite corresponds to a temperature range of 1000°C to 900°C and is indistinguishable with that (1100°C to 900°C) of the phenocrystic clinopyroxene in host lamprophyres (see Table 1) with both of them displaying an overlap with the stability field of high Ca-pyroxene (Figure 5A). Occurrence of clinopyroxenes in igneous rocks is also sensitive to

the pressure of crystallization (Nimis 1995) and can be applicable to determine the crystallization conditions of alkaline ultramafic magma such as lamprophyres following the clinopyroxene geobarometric formulation of Putirka (2008). Geobarometric calculations based on Putirka [2008, Equation (1) below] using the composition of clinopyroxenes from megacrystic suite and phenocrysts of this study indicate an overlapping range of crystallization pressure between 9.8 to 12.4 kbar and 8.4 to 10.1 kbar, respectively (Table 1).

$$P \text{ (kbar)} = 3205 + 0.384 \cdot (T + 273.15) - 518 \cdot \ln(T + 273.15) - 5.62 \cdot \text{Mg} + 83.2 \cdot \text{Na} + 68.2 \cdot \text{DiHd} + 2.52 \cdot \text{Al}^{\text{VI}} - 51.1 \cdot \text{DiHd}^2 + 34.8 \cdot \text{EnFs}^2 \quad (1)$$

where T is in °C; cations in clinopyroxene formula calculated on 6 oxygen basis;

$$\text{Al}^{\text{IV}} = 2 - \text{Si}; \text{Al}^{\text{VI}} = \text{Al} - \text{Al}^{\text{IV}};$$

Jd = Al<sup>VI</sup> or Na, whichever is less; if excess Al<sup>IV</sup> remains after forming Jd;

$$\text{CaTs} = \text{Al}^{\text{IV}} - \text{Jd}, \text{ if } \text{Al}^{\text{IV}} > \text{CaTs}; \text{CaTi} = (\text{Al}^{\text{IV}} - \text{CaTs})/2;$$

$$\text{CrCaTs} = \text{Cr}/2;$$

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**Table 1.** Mineral chemistry (oxide wt%) of the clinopyroxene from the megacryst suite and host lamprophyre of this study. Pressure estimation based on Putirka (2008) in equation (1) at 1000°C temperature.

	Megacryst suite					Lamprophyre (Phenocrysts)				
	PP/U1/4									
SiO <sub>2</sub>	45.40	46.86	46.76	45.12	46.10	45.80	50.21	46.36	46.65	47.22
TiO <sub>2</sub>	1.69	2.17	2.32	2.28	1.94	3.12	0.89	2.59	2.39	2.22
Al <sub>2</sub> O <sub>3</sub>	8.22	8.39	7.79	8.03	8.23	8.57	6.39	8.55	7.86	7.93
Cr <sub>2</sub> O <sub>3</sub>	0.03	0.08	0.11	0.01	0.01	0.10	0.37	0.03	0.00	0.03
FeO	8.92	8.42	8.38	8.99	8.24	6.77	4.97	7.08	6.62	6.77
MnO	0.26	0.00	0.13	0.06	0.00	0.15	0.05	0.22	0.25	0.04
MgO	10.94	11.06	11.45	10.90	11.23	12.36	14.97	12.37	12.72	12.99
CaO	22.80	21.70	22.04	22.73	22.78	21.78	20.42	21.44	22.06	21.45
Na <sub>2</sub> O	0.99	1.19	0.87	1.06	0.85	0.70	0.87	0.90	0.80	0.69
K <sub>2</sub> O	0.01	0.04	0.08	0.00	0.01	0.00	0.06	0.00	0.00	0.00
Total	99.26	99.91	99.94	99.18	99.41	99.33	99.21	99.56	99.34	99.33
Cations for 6 oxygen atoms										
Si	1.732	1.759	1.758	1.724	1.744	1.720	1.851	1.737	1.751	1.765
Ti	0.048	0.061	0.066	0.065	0.055	0.088	0.025	0.073	0.067	0.062
Al	0.370	0.371	0.345	0.361	0.367	0.379	0.278	0.377	0.347	0.349
Cr	0.001	0.002	0.003	0.000	0.000	0.003	0.011	0.001	0.000	0.001
Fe <sub>t</sub>	0.265	0.264	0.263	0.237	0.261	0.212	0.153	0.222	0.208	0.212
Mn	0.008	0.000	0.004	0.002	0.000	0.005	0.002	0.007	0.008	0.001
Mg	0.622	0.619	0.642	0.621	0.634	0.692	0.823	0.691	0.711	0.724
Ca	0.932	0.873	0.888	0.930	0.923	0.876	0.806	0.860	0.887	0.859
Na	0.074	0.086	0.063	0.078	0.062	0.051	0.062	0.066	0.058	0.050
K	0.000	0.002	0.004	0.000	0.001	0.000	0.003	0.000	0.000	0.000
Total	4	4	4	4	4	4	4	4	4	4
Wo	48.64	47.43	47.78	48.61	49.20	47.76	43.68	46.66	47.43	46.56
En	32.49	33.64	34.54	32.44	33.76	37.72	44.58	37.47	38.04	39.26
Fs	15.03	14.23	14.28	14.85	13.73	11.76	8.36	12.31	11.42	11.48
Ac	3.84	4.69	3.40	4.10	3.32	2.76	3.38	3.55	3.11	2.70
Mg#	0.90	0.80	0.81	0.89	0.85	0.84	0.88	0.85	0.88	0.84
Ca/(Ca+Mg)	0.60	0.59	0.58	0.60	0.59	0.56	0.49	0.55	0.55	0.54
P (kbar)	10.7	12.4	9.8	10.5	9.8	8.4	9.6	10.1	9.0	8.7

DiHd = Ca - CaTi - CaTs - CrCaTs; and EnFs = (Fe + Mg - DiHd)/2;

### Ti-in-Biotite Geothermometry

Biotite composition from the megacrystic suite and phenocrystic phase of Udiripikonda lamprophyre are essentially confined to the primary biotite field (see also Figure 5B; Nacht et al., 1985). It has been highlighted before, that TiO<sub>2</sub> content in biotites from megacrystic suite is relatively higher in comparison to phenocrystic biotites from host lamprophyres. Experimental investigations have demonstrated that Ti solubility in mica increases with temperature and decreases with pressure (Robert

1976). As a result, Ti substitution in biotite can be very useful in geothermometric estimation (Henry et al., 2005). Recently, Wu and Chen (2015) proposed Ti-in-biotite geothermometry based on empirical calibration over a wide range of pressure conditions [Equation (2) below].

$$T (^{\circ}\text{C}) = \text{Exp}[6.313 + 0.224 \cdot \ln(X_{\text{Ti}}) - 0.228 \cdot \ln(X_{\text{Fe}}) - 0.499 \cdot \ln(X_{\text{Mg}}) + 1.5 \cdot P] \quad (2)$$

Where P is in kbar; cations in biotite formula calculated on 22 oxygen basis;

$$X_Z = Z / (\text{Fe} + \text{Mg} + \text{Al}^{\text{VI}} + \text{Ti}),$$

Z = Fe, Mg, Ti;

Calculation of Ti-in-biotite geothermometry suggests an overlapping temperature range of 957°C to 1097°C and 904°C to 1069°C for megacrystic suite and phenocrysts

**Table 2.** Mineral chemistry (oxide wt%) of the micas from megacryst suite and host lamprophyre of this study. Temperature estimation based on the formulation of Wu and Chen (2015) in equation (2) at 10 kbar pressure.

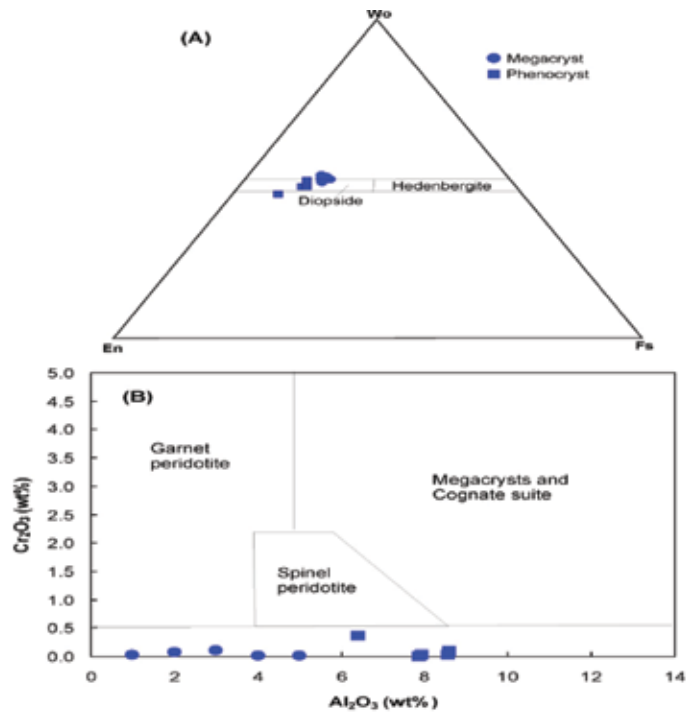
	Megacryst suite					Lamprophyre (Phenocrysts)				
	PP/U1/4									
SiO <sub>2</sub>	34.59	34.07	35.32	33.60	34.89	34.12	32.41	31.55	29.85	31.56
TiO <sub>2</sub>	11.89	7.64	7.08	10.19	7.00	4.77	5.89	8.76	7.81	8.07
Al <sub>2</sub> O <sub>3</sub>	13.28	14.62	13.60	13.92	14.33	13.67	13.77	12.65	12.84	13.73
Cr <sub>2</sub> O <sub>3</sub>	0.05	0.11	0.09	0.07	0.10	0.00	0.00	0.00	0.00	0.00
FeO	13.96	16.88	18.73	18.37	19.17	21.00	21.02	22.17	21.72	20.86
MnO	0.10	0.00	0.00	0.08	0.06	0.12	0.21	0.46	0.45	0.33
MgO	12.24	10.67	10.14	9.46	9.43	8.06	8.41	7.81	7.90	8.33
CaO	0.20	0.07	0.17	0.10	0.05	0.41	0.63	0.73	3.09	0.38
BaO	0.55	0.73	0.51	0.11	0.18	0.19	0.21	0.14	0.19	0.14
Na <sub>2</sub> O	0.49	0.27	0.36	0.29	0.32	0.68	0.20	0.39	0.21	0.31
K <sub>2</sub> O	8.24	8.96	8.54	8.22	8.59	7.76	7.68	6.88	6.96	7.46
F	0.42	0.44	0.24	0.09	0.20	0.00	0.00	0.00	0.00	0.06
Total	96.00	94.46	94.80	94.50	94.32	90.80	90.42	91.55	91.00	91.22
Cations for 22 oxygen atoms										
Si	5.186	5.280	5.457	5.190	5.412	5.544	5.315	5.149	4.957	5.136
Al	2.347	2.671	2.476	2.535	2.588	2.456	2.661	2.433	2.513	2.633
Cr	0.006	0.013	0.011	0.008	0.013	0.000	0.000	0.000	0.000	0.000
Al	0.000	0.000	0.000	0.000	0.033	0.162	0.000	0.000	0.000	0.000
Ti	1.340	0.890	0.823	1.184	0.817	0.584	0.727	1.075	0.975	0.988
Fe(ii)	1.750	2.187	2.419	2.373	2.487	2.853	2.882	3.025	3.016	2.838
Mn	0.012	0.000	0.000	0.011	0.008	0.016	0.030	0.063	0.063	0.046
Ba	0.032	0.045	0.031	0.006	0.011	0.012	0.013	0.009	0.012	0.009
Mg	2.735	2.465	2.336	2.178	2.181	1.952	2.055	1.899	1.955	2.020
Ca	0.031	0.011	0.028	0.017	0.008	0.072	0.111	0.127	0.549	0.065
Na	0.141	0.082	0.109	0.086	0.095	0.214	0.063	0.124	0.067	0.097
K	1.576	1.772	1.683	1.619	1.699	1.609	1.607	1.433	1.474	1.549
F	0.197	0.213	0.118	0.046	0.100	0.000	0.000	0.000	0.000	0.033
Total	15.354	15.628	15.491	15.253	15.451	15.475	15.463	15.338	15.582	15.415
Mg#	0.61	0.53	0.49	0.48	0.47	0.41	0.42	0.39	0.39	0.42
T (°C)	1097	988	957	1090	978	904	954	1069	1035	1042

respectively (see Table 2), at a pressure of ~10 kbar, which is obtained from clinopyroxene geobarometry.

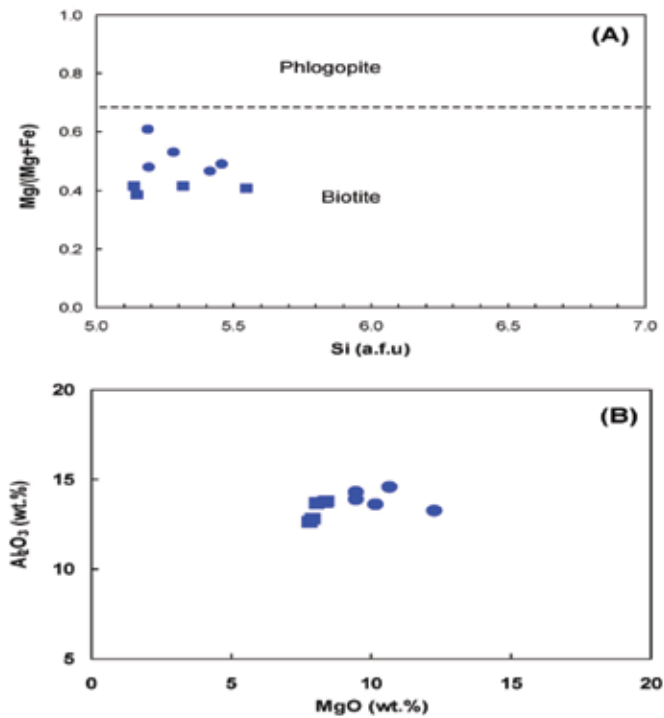
Rock (1991) highlighted two important criteria to distinguish between a xenocrystic/xenolithic and cognate origin of the megacrysts found in the lamprophyres: (i) compositional disparity with the equivalent minerals in the groundmass, and (ii) presence of reaction rims or resorption features in case of xenocrysts. A compositional similarity between the megacrystic and liquidus phases and lack of disequilibrium textures rule out a xenocrystic/xenolithic origin of the megacrysts, in this study, and instead imply their genetic relation with the lamprophyre. This is further

supported by the fact that the mica reported from mantle-derived xenoliths is typically a phlogopite rather a biotite and absence of any deformation in the megacrysts (see O'Reilly and Griffin, 2013). Note that deformation is a common, but not essential, feature of many of the studied mantle-derived xenoliths and xenocrysts. A cumulate-origin for the megacrysts is also not favoured owing to the strong compositional overlap displayed by the diopsides of the two paragenesis. Pressure-temperature estimates on the clinopyroxene and biotite from megacrysts and phenocrysts (above) reveal their overlapping characteristics. A relative paucity of Ba and F in the groundmass mica (see Table

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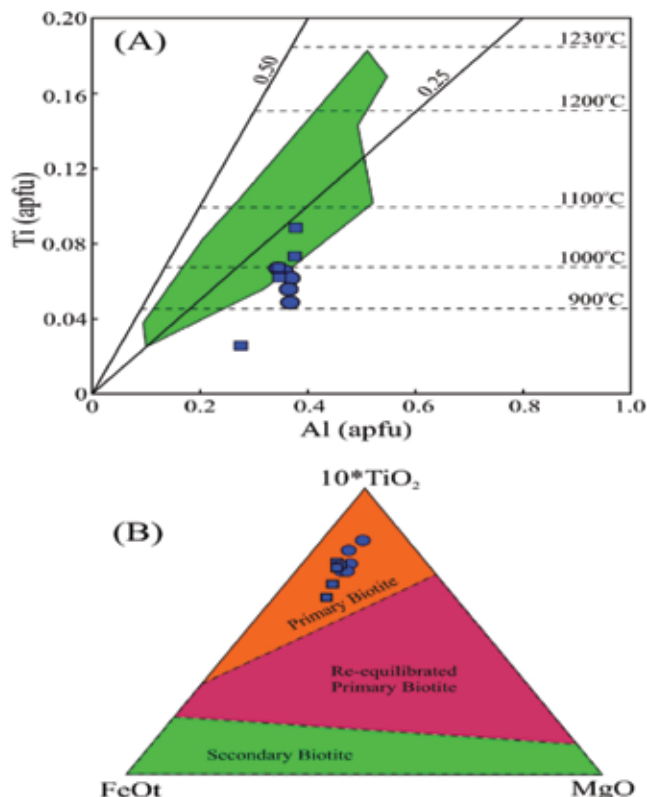


**Figure 3.** (A) Diopsidic nature of the megacrystic and phenocrystic clinopyroxene in the standard pyroxene ternary plot. Note their compositional similarity. (B) Al<sub>2</sub>O<sub>3</sub> (wt%) versus Cr<sub>2</sub>O<sub>3</sub> (wt%) of the clinopyroxene megacrysts and phenocrysts of this study in the compositional fields of clinopyroxene xenocrysts, megacrysts and cognate suite found in kimberlites (after Ramsay, 1992). Note the conspicuously lower chromium contents of the megacrysts as well as phenocrysts of this study. Symbols remain the same as in Figure 3A.



**Figure 4.** (A) Si (atoms per formula unit) versus Mg/(Mg+Fe) mica classification diagram (after Reider et al., 1998) for the megacrystic and phenocrystic micas from this study. (B) MgO (wt%) versus Al<sub>2</sub>O<sub>3</sub> (wt%) binary plot of the biotites of this study showing their overall compositional similarity. Symbols remain the same as in Figure 3A.





**Figure 5.** (A) Ti versus Al contents (atoms per formula unit) diagram with the stability field of high Ca-pyroxene (after Gerke et al., 2005) for megacrystic and phenocrystic clinopyroxene from this study. (B) Primary nature of biotite from the TiO<sub>2</sub>-FeO-MgO triangular diagram (after Nachit et al., 1985) for the megacrystic and phenocrystic micas from this study. Symbols remain the same as in Figure 3A.

2), perhaps, reflects the depletion of these elements in the lamprophyre melt due to their incorporation whilst crystallization of the earlier formed megacrysts. Possible early crystallization of the clinopyroxene megacrysts is also indicated by the sub-rounded nature (Figure 1 and 2) reflecting the abrasion during the ascent of the lamprophyre magma. Further studies, deploying multi-instrumental analytical techniques such as LA-ICP-MS, on these megacrystic nodules from Udiripikonda lamprophyre are required to firmly ascertain and constrain their genesis.

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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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