Almandine megacrysts from Yingfengling Cenozoic basalt in Leizhou Peninsula and their parental magma origin

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Abstract The garnet megacrysts from Yingfengling basalts are characterized by high FeO (>20%), CaO (7.02% --8.16%) and low MgO (5.88%--10.87%). Significant composition variations are observed in these megacrysts, of which Ni, V, Sc, Co, and HREE are positively correlated with their Mg[#], and Zr, Hf, Ga, Y, Sr, Nb, Zn and LREE-MREE are negatively correlated with Mg[#]. Megacryst parent magma is a highly evolved residual melt with strongl depletion in Ti, Sr, Hf, Nb and HREE. This parental magma was generated by more than 60% of crystallization fractionation of clinopyroxene, garnet, plagioclase and ilmenite from quartz tholeiitic magma. It has not erupted to the surface, but stayed at the upper mantle and formed the megacrystic cumulate. Megacrysts and their host basalt are in disequilibrium.

Keywords: almandine megacryst, geochemistry, LAM-ICPMS, Leizhou Peninsula.

Cenozoic basalts frequently contain varied megacrystic minerals, which have been used to reveal the geochemical behavior and evolution of the basaltic liquid in the deep mantle^[1-4]. Garnet megacryst is important and relatively sparse. Its occurrence reflects the megacrysts forming in deeper mantle (>2.0 GPa)^[1]. Garnet megacrysts have been also found at some Cenozoic basalts in eastern China^[5-8]. However, these garnets are of pyrope as those in kimberlites. This note will report the almandine megacrysts found in Yingfengling volcano, study their geochemical characteristics using the LAM-ICPMS technique, and speculate on the origin of the megacryst parental melt.

1 Fundamental geology and megacryst petrography

Yingfengling volcano is located in the center of Leizhou Peninsula, South China (21.5°N, 110.2°E), which contains abundant deep-seated xenoliths and megacrysts^[9,10]. The megacrysts in Yingfengling basalt include garnet, clinopyroxene, plagioclase, ilmenite and apatite. Most megacrysts occur as discrete ones, some as composite megacrysts or megacryst aggregates. Aggregate megacryst is smaller in grain size, however, identical with the discrete megacryst in composition. Garnet megacrysts are dark red-brown to orange yellow, mostly 3—4 cm in size, and a few bigger than 8 cm.

2 Garnet megacryst compositions

All analyses of the megacryst compositions were carried out at National Key Center of GEMOC in Macquarie University, Australia. Major element compositions were determined with a Cameca-SX50 electron microprobe. Trace element analysis was carried out using the laser ablation microprobe inductively coupled plasma mass spectrometer (LAM-ICPMS). The analytical technique, conditions and precision are the same as those described by Norman et al.^[11].

Microprobe analyses of more than seven points for each sample show that garnet composition is very homogeneous in a megacryst grain or different grains in an aggregate. However, the remarked composition variation is observed among different, discrete megacryst grains. As the $Mg^{\#}$ of garnet decreases, Fe and Mn contents considerably increase, and Mg, Al and Ti gradually decrease (table 1). Ca seems not closely related to Mg# change^[10]. In comparison with those garnet megacrysts from other locations, Yingfengling garnets have significantly high FeO and CaO content (fig. 1). They contain grossular component of 40%—54%, pyrope 23%—41% and andradite 19%—23%. So these garnets can be described as Mg, Ca-rich almandine.



Fig. 1. The plot of $Mg^{\#}$ against CaO content of the garnet megacrysts from Leizhou and other localities in eastern China. All data, except Leizhou, are from refs. [5–8].

3 Trace element features

Trace element compositions of almandine megacrysts are also homogeneous, like their major elements. Compared with the pyrope megacryst from alkaline basalt in Tsavarin-Tsharam of NW Mongolia, Yingfengling almandine megacrysts have lower V, Ni, Sc, Zr, Hf and Nb concentrations, and same Y, Sr, Ga and LREE contents. Of them V, Ni and Sc contents clearly decrease with Mg[#] decrease (table 2), while Y, Sr, Ga and LREE increase as Mg[#] decrease (table 2). The most peculiar geochemical characteristic of Yingfengling almandine megacryst is their arch REE patterns with intense depletion of LREE

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Sample	Lzgt-19	Lzgt-24	Lzgt-11	Lzgt-22	Lzgt-17	Lz-54*	Lz-17*	Lzgt-14*	Lz-24*	Lz-27*	Mongol	LZB
Average No.	8	9	12	10	8	16	7	9	3	16		3
SiO ₂	39.14	39.20	38.95	38.21	38.34	39.52	38.66	38.33	38.50	37.89	40.37	53.23
TiO ₂	0.74	0.70	0.63	0.37	0.37	0.59	0.58	0.61	0.55	0.43	0.62	1.47
Al_2O_3	21.54	21.55	21.80	20.90	20.76	21.76	21.28	21.01	21.26	20.66	22.35	15.10
Cr_2O_3	0.02	0.02	0.02	0.00	0.02	0.01	0.01	0.01	0.02	0.02	0.02	1.82*
FeO ^t	20.95	21.36	22.83	25.71	26.46	20.07	22.73	24.03	24.43	26.50	15.87	7.83
MnO	0.41	0.42	0.41	0.44	0.52	0.39	0.46	0.46	0.46	0.46	0.41	0.14
MgO	10.00	9.46	8.12	6.45	6.28	10.87	8.52	7.00	6.84	5.88	15.09	7.13
CaO	7.18	7.68	8.05	7.05	7.32	6.92	7.67	8.16	8.02	7.59	5.52	8.80
Na ₂ O	0.07	0.05	0.06	0.03	0.05	0.04	0.04	0.07	0.04	0.07	0.05	2.94
Si	2.972	2.973	2.965	2.997	2.991	2.979	2.970	2.978	2.979	2.982	2.967	
Al	1.928	1.927	1.956	1.932	1.910	1.933	1.927	1.924	1.939	1.916	1.936	
Ti	0.042	0.040	0.036	0.022	0.022	0.033	0.033	0.035	0.032	0.025	0.034	
Cr	0.001	0.001	0.001	0.000	0.001	0.001	0.000	0.000	0.001	0.001	0.001	
Fe	1.330	1.355	1.453	1.686	1.727	1.265	1.461	1.561	1.581	1.744	0.975	
Mn	0.026	0.027	0.026	0.029	0.034	0.025	0.030	0.030	0.030	0.031	0.026	
Mg	1.132	1.070	0.922	0.754	0.730	1.221	0.976	0.810	0.788	0.690	1.653	
Ca	0.584	0.624	0.657	0.593	0.612	0.559	0.631	0.679	0.665	0.640	0.435	
Na	0.010	0.007	0.008	0.005	0.007	0.006	0.006	0.011	0.006	0.010	0.007	
Mg [#] (gt)	0.46	0.44	0.39	0.31	0.30	0.49	0.40	0.34	0.33	0.28	0.63	
Alm	41.8	42.6	46.2	54.3	54.1	39.8	45.2	49.2	50.5	54.4	29.2	
Spss	0.9	0.9	0.9	1.0	1.1	0.8	1.0	1.0	1.0	1.0	0.9	
Pyrope	37.8	35.7	30.9	25.1	24.3	40.7	32.6	27.1	26.3	23.1	55.4	
Gros	19.5	20.8	22.0	19.7	20.4	18.7	21.1	22.7	22.2	21.4	14.6	
Mg [#] (cpx)						0.62	0.57	0.53	0.53	0.48		
Mg#(melt)						0.27	0.22	0.19	0.19	0.16		0.57

-f = -1 + -1

The samples with * label are megacryst aggregate. Mongol is a pyrope from Mongolia, its EMP data were given by Prof. Griffin. LZB is host quartz tholeiite, its K₂O is 0.63% and datum in Cr₂O₃ row is Fe₂O₃ content. All iron of garnet megacryst is expressed as FeO¹. Structural formula is calculated based on 12-oxygen ion. Fe³⁺ obtained in the light of charge balance is about 5.7% of all iron, therefore neglecting Fe³⁺ does not significantly affect the conclusion in this text. Mg[#]=Mg/(Mg+Fe) (mol). Mg[#] (cpx) is for clinopyroxene in related aggregate; Mg[#] (melt) is that of the calculated parental melt or host basalt.



Fig. 2. REE patterns of Yingfengling megacrystic garnets.

and HREE and enrichment of MREE (fig. 2). Fig. 2 shows that LREE and MREE (La-Ho) are negatively correlated

with Mg[#], and HREE (Tm, Yb, Lu) are positively correlated with Mg[#]. Er contents nearly maintain constant. Relative to those pyrope megacrysts from Huangyishan, NE China^[3] and Tsavarin-Tsharam, NW Mongolia, Yingfengling garnet megacrysts have similar LREE, higher MREE and strongly depleted HREE (Er-Lu) (fig. 2). In the primitive mantle normalized spidergram (not shown here), almandine megacrysts show clearly Ti, Sr, Nb, Zr and Hf negative anomalies.

4 Characteristics of megacryst parent melt

 $Mg^{\#}$ of Yingfengling garnets is low ranging from 0.28 to 0.49, and that of the clinopyroxenes in megacryst aggregates ranges from 0.48 to 0.62 (table 1). In the megacryst aggregate, the $Mg^{\#}$ of garnet and clinopyroxene shows a good relationship and trace element partition coefficients between them have a little and regular change,

Table 2 Trace element compositions of Yingfengling garnet megacrysts and their host basalt $(\mu g/g)$

Sample No.	Lzgt-19	Lzgt-24	Lzgt-11	Lzgt-22	Lzgt-17	Lz-54*	Lz-17*	Lzgt-14*	Lz-24*	Lz-27*	Mongol	LZB
Average No.	5	5	9	9	5	2	3	5	2	3	13	3
Sc	18.06	14.22	9.49	5.01	5.28	19.42	11.74	6.42	7.35	4.74	44.11	20.68
Ti	3823	3921	3690	2183	2141	3087	3371	3138	3029	2401	3486.3	8960
V	143.4	128.0	105.3	38.4	28.8	116.1	99.4	71.8	71.9	38.8	154.7	140.8
Co	81.56	76.04	73.17	66.99	66.00	78.50	76.35	61.99	69.00	62.82	72.23	43.68
Ni	10.72	6.36	3.10	4.11	2.97	14.06	9.46	2.13	3.00	2.12	27.71	188.57
Zn	73.42	69.70	69.96	116.69	136.91	72.27	82.79	92.58	93.30	129.99	42.64	89.36
Ga	10.76	11.02	10.99	14.98	15.64	9.84	11.45	13.24	13.50	15.96	9.20	17.79
Sr	0.40	0.50	0.53	0.49	0.50	0.35	0.61	0.60	0.68	0.54	0.47	293.28
Y	60.30	69.20	61.87	71.87	72.32	53.86	66.53	71.81	68.15	72.41	59.35	17.41
Zr	45.64	58.62	51.03	57.78	52.37	33.46	45.60	56.59	48.50	50.30	61.40	89.14
Nb	0.045	0.040	< 0.082	0.070	0.046	0.041	< 0.090	0.043	0.050	0.040	0.06	9.35
La	0.040	0.040	0.065	0.058	0.050	< 0.013	< 0.081	0.038	0.045	0.048	0.06	8.31
Ce	0.25	0.31	0.35	0.60	0.58	0.19	0.56	0.46	0.48	0.61	0.28	17.07
Pr	0.12	0.14	0.17	0.29	0.28	0.08	0.15	0.22	0.20	0.28	0.11	2.44
Nd	1.50	1.94	2.16	4.00	4.07	1.28	2.34	2.94	2.95	4.04	1.48	10.83
Sm	2.20	2.88	3.22	6.13	6.02	1.82	3.12	4.26	4.35	5.90	1.83	3.21
Eu	1.41	1.76	2.08	3.83	3.76	1.26	2.13	2.64	2.65	3.52	1.14	1.26
Gd	6.70	8.32	9.60	16.74	15.51	5.54	9.27	11.34	11.95	15.55	4.82	3.59
Tb	1.63	2.06	2.20	3.56	3.45	1.43	2.10	2.69	2.75	3.37	1.27	0.56
Dy	12.10	14.06	14.32	20.41	20.15	10.58	14.99	16.36	17.05	20.28	9.81	3.18
Но	2.52	2.88	2.60	3.03	3.13	2.20	2.84	2.79	3.00	3.13	2.33	0.63
Er	5.52	6.14	4.98	4.52	5.00	5.26	5.84	4.97	5.45	5.13	6.49	1.63
Tm	0.60	0.63	0.46	0.33	0.38	0.57	0.60	0.42	0.46	0.40	0.87	
Yb	3.04	2.96	1.79	1.16	1.41	3.02	2.65	1.70	1.81	1.46	5.42	1.30
Lu	0.31	0.27	0.17	0.08	0.10	0.30	0.21	0.13	0.16	0.10	0.71	0.18
Hf	0.83	1.05	0.84	0.87	0.78	0.60	0.84	0.88	0.83	0.79	1.14	2.22
Th	0.019	0.012	< 0.022	0.016	0.007	< 0.012	< 0.019	0.008	< 0.009	< 0.007	0.010	1.50
U	< 0.020	0.017	0.016	0.020	0.008	0.006	0.017	0.007	0.010	< 0.006	< 0.018	0.36

Data for Mongolian pyrope megacryst are analyzed with LAM-ICPMS in this study, LZB is analyzed with the solution ICP-MS method.

suggesting that garnet and clinopyroxene are in equilibrium. Temperature and pressure calculations also indicate that crystallization temperature is positively correlated with $Mg^{\#[10]}$, implying that the megacryst aggregate is not an occasional assembly of the minerals with different origins. Thus the $Mg^{\#}$ of garnet parent melt can be estimated based on the composition of the coeval clinopyroxene in megacrystic aggregate and Wood's calculation equation^[12]. Calculations indicate that $Mg^{\#}$ of their parental liquids is 0.27 - 0.16 from Mg-rich endmember to Fe-rich one. This means that the megacryst parental melt will contain much low MgO (about 2.5%-3.5%), even if assuming it has high FeO^t (12%-17%). Due to very high $Mg^{\#}$ of host basalt (0.57, table 1), it is suggested that host melt is not megacryst parental liquid.

By using the partition coefficients between garnet and melt^[13], the trace element characteristics of the parent melt can be brought to light (figs. 3 and 4). The calcula-

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tion results show that the parent melt of Yingfengling megacrysts is rich in REE, ranging from 107 to 308 μ g/g (those rare earth elements of unavailable partition coefficients are estimated with interpolation). Their REEs are significantly differentiated with LREE enrichment and intense HREE depletion, even Lu lower than HREE of chondrite (fig. 3).

In the spidergram of the primitive mantle normalized trace elements abundance (fig. 4), the megacryst parent melts show the remarked Nb, Sr, Zr, Hf, Ti and HREE (Yb, Lu) anomalies. The relative depletion of these elements is closely related with fractional crystallization of garnet, ilmenite, plagioclase and apatite, because these minerals are most important carriers of above- mentioned elements and they have been found in the Yingfengling volcano. It is suggested that the parental melt had undergone fractional crystallization of garnet, clinopyroxene, ilmenite and plagioclase without apatite before Lz-54

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Fig. 3. The REE patterns of the parent melts of garnet megacrysts. Legends are the same as in fig. 2.



Fig. 4. Primitive mantle normalized trace element abundance of the parent melts of Yingfengling garnet megacrysts. Legends are the same as in fig. 2.

5 The origin of parental magma

Coeval crystallization of garnet, clinopyroxene, plagioclase and ilmenite indicate their parental melt of basic or intermediate-basic one. However, in Leizhou Peninsula and Hainan Island (Lei-Qiong area) such low Mg[#] (0.27—0.16) and depleted HREE volcanic rocks have not been found^[14—16], implying that this melt did not erupt to the surface, but detained in upper mantle and solidified. P-T estimations indicate that the crystallization takes place at 1270—1130°C and >1.5 GPa^[10].

Above-mentioned geochemical characteristics indicate that the formation of megacryst parent melt must experience fractional crystallization. The fact that the various degrees of partial melting of the mantle peridotites with different compositions under any experiment conditions cannot directly produce the melt with FeO of >12% and MgO of <5% also imply that such low Mg[#] melt result from strong crystallization differentiation ^[17]. Then, which kind of magma is the primary melt of megacryst parent rock? Several basalts found in the Lei-Qiong area have been tested as primary magma to model the fractional crystallization process. Equation $C_L = C_0 \times F^{(D-1)}$ for

Rayleigh fractionation was used here, where C_0 is the weight concentration of a trace element in the parental liquid, $C_{\rm L}$ is the weight concentration of a trace element in the liquid, F is the fraction of melt remaining, and D is bulk partition coefficient of the fractionating assemblage during crystal fractionation. The partition coefficients for garnet and clinopyroxene are from the experimental data of Johnson et al.^[13]. Partition coefficients of the trace elements between oligoclase and melt are obtained according to the partition of plagioclase and garnet in megacryst aggregate $(D_{pl/gl})$ and the given $D_{gl/melt}$. REE partition co-efficients for ilmenite are from Paster's data^[18]. Bulk partition coefficient is calculated by using the proportion of garnet/clinopyroxene/plagioclase/ilmenite of $5 \div 8 \div 6 \div 1$. This proportion is determined based on the field statistics of varied megacrysts occurred in Yingfengling volcanic rock, the proportion of minerals in aggregate and in consideration of trace element variation tendency of the megacryst minerals. Because the proportion of the crystallizing minerals during fractional crystallization is probably varied, the modeling in this study is average. Modeling indicates that the primary magma of megacryst parent melt is probably a quartz tholeiitic one compositionally similar to Yingfengling host basalt (table 1, fig. 5). The parental melt of Lz-54 megacryst, which is the richest magnesium one within all Yingfengling megacrysts, can be produced from quartz tholeiitic magma through about 60%—70% (F = 0.3—0.4) crystal fractionation (fig. 5).



Fig. 5. REE pattern comparison of the parent melt of Lz-54 megacryst with those melts generated by fractional crystallization modeling of quartz tholeiitic magma.

Olivine tholeiite, alkali olivine basalt and basanite have higher HREE than the parent melt of the Lz-54 garnet megacryst, and higher or similar LREE concentrations. Because the crystallization fractionation of the garnet and so on will lead to LREE content increase as well as HREE content decrease, these magmas cannot be the primary liquid of Yingfengling garnet.

6 Discussion and conclusion

Yingfengling garnet megacryst is a rare almandine featured by high FeO and CaO and low MgO. They have large composition variation in major and trace elements, reflecting a long crystallization process. With the decreasing of the magnesium number of garnets, Ni, V, Sc, Ti, Co and HREE (Tm, Yb, Lu) are decreasing, and Zr, Hf, Ga, Y, Sr, Nb, Th, U, Zn, and LREE-MREE (La-Ho) are increasing. The composition variations of the garnet megacrysts depend on the composition variation of their parent melt, and the composition change of the parent melt results evidently from the crystallization fractionation. It is required that the parent melt is a residual liquid with small volume, so that some amount of crystal fractionation can lead to the remarked change of trace element concentration in the magma remaining. On the other hand, fractional crystallization modeling has confirmed that the parental melt of Lz-54 megacryst was generated from quartz tholeiitic magma by 60%-70% fractionation, and the formation of parental melt of Lz-27 megacryst (lowest Mg[#] endmember) needs 80%—90% crystal fractionation. All these evidence that Yingfengling megacrysts were crystallized from a highly evolved, residual magma. The host is not their parent magma, i.e. the host and megacrysts are in disequilibrium. Hence the trace element concentrations of megacryst and host basalt cannot be utilized to calculate the partition coefficients. This evolved parent magma does not erupt to the surface, and appears to be hidden in upper mantle and crystallize to megacrystic cumulate or dyke. The host was formed later than the primary magma of megacrysts, and captured the crystallized megacrysts during its uplifting.

Because more primitive and Mg-richer megacrysts or aggregates have not been found, early fractional crystallization of original magma probably took place at deeper and different magma chambers from late crystallization environment of residual melt.

If the primary magma of Yingfengling megacrysts is more depleted N-MORB more crystal fractionation is needed to form the parental melt of Lz-54 megacryst. The early crystallization of N-MORB probably involved olivine. Its fractionation will give rise to Mg[#] decrease and REE and other incompatible element increase of magma remaining. As the evolving magma becomes silica saturation, clinopyroxene, garnet and plagioclase are growing principal crystallization phases.

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