Silica minerals and pyroxenes in the Camel Donga non-cumulate eucrite: Further evidence for its polymict nature

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Introduction: It is widely considered that the HED (Howardite-Eucrite-Diogenite) meteorite group originates from the asteroid 4 Vesta and eucrite formed its crust [e.g., 1]. Eucrite is roughly classified into two subgroups: cumulate and non-cumulate. Non-cumulate eucrites are basaltic rocks probably formed near the surface of Vesta and divided into types 1-7 by thermal metamorphic degrees [2]. We have so far studied silica minerals in eucrites to understand their formation conditions, especially thermal histories at low temperature below 400 °C [e.g., 3,4]. In our previous studies, we have found that assemblage of silica minerals is correlated with thermal metamorphic levels [e.g., 5]. Particularly, each clast in polymict non-cumulate eucrites clearly reflects such correlations. For example, Yamato-75011 is a polymict non-cumulate eucrite and has various combinations of silica minerals in basaltic clasts [6]. Therefore, identifying silica minerals in basaltic clasts in brecciated eucrites will be useful to determine whether they are monomict or polymict because it is sometimes difficult to tell it only from pyroxene mineralogy. To test the usefulness of silica minerals to determine the nature of brecciated eucrites, we selected Camel Donga in this study because it is classified as a monomict eucrite (Meteoritical Bulletin Database), but a recent study pointed out a possibility of the polymict nature because of the presence of groundmass metal and some metal nodules [7]. We determined silica phases in basaltic clasts of this eucrite as well as chemical compositions of pyroxenes to further discuss the relationship between the thermal metamorphic levels and silica mineralogy.

Sample: We studied a polished thick section of Camel Donga (*ca*. 22 mm x 11 mm). Camel Donga is classified as a monomict brecciated eucrite and considered to be type 5 [8] in the thermal metamorphism classification of Takeda and Graham [2].

Methods: The section was analyzed with the JEOL JXA-8200 electron microprobe at NIPR to measure the chemical composition of pyroxene. Micro Raman spectra of silica phases were obtained by the JASCO NRS-1000 at NIPR. We obtained electron back-scattered diffraction (EBSD) patterns of silica minerals using a FIB-SEM (Thermo Fisher Scientific Quanta 200 3DS) at Kyoto University to confirm the phase identification of silica minerals.

Result and Discussion: We studied 6 basaltic clasts in the Camel Donga eucrite. They can be classified into 3 groups by pyroxene chemical compositions as follows: (A) clasts containing orthopyroxene having Mg-Fe zoning ($En_{38}Wo_{2}$~$En_{42}Wo_{4}$); (B) clasts containing homogeneous orthopyroxene and augite ($En_{39}Wo_{2}$~$En_{31}Wo_{44}$); (C) clast containing augite having Mg-Fe chemical zoning ($En_{32}Wo_{38}$~$En_{31}Wo_{44}$). We show pyroxene compositions of 6 clasts in Figure 1. Their thermal metamorphic degrees based on pyroxene chemical compositions [2] are type 4 for (A) and (C) clasts, and type 5-6 for (B) clast. The silica mineralogy of these basaltic clasts can be also classified into 3 groups; (a) aggregates of orthorhombic tridymite and quartz, (b) aggregates of monoclinic tridymite and quartz, and (c) only quartz. We summarize these observations in Table 1. Although these independent classifications are not necessarily corresponding to each other, they show a general correlation. For example, no monoclinic tridymite is contained in clasts which include pyroxene with chemical zoning. It indicates that clasts 3 and 6 have experienced thermal metamorphism at high temperature with subsequent slower cooling processes than other groups (without monoclinic tridymite and containing pyroxene with chemical zoning) at least below 400 °C because of the presence of monoclinic tridymite. Therefore, we can consider that high-metamorphic eucrites include monoclinic tridymite as seen in Agoult and Ibitira [5]. On the other hand, silica-group (c) (containing only quartz) has two types of quartz with different occurrences. One type is found in clast 4 and quartz is located between plagioclase crystals, and the other type is found in clasts 2 and 5 and quartz is enclosed in pyroxene (Fig. 2). The former is similar to the quartz occurrence in Stannern, type 4 non-cumulate eucrite (Fig. 2). Therefore, we consider that clast 4 formed under the similar condition to Stannern and clasts 2 and 5 share the same origin in the Vesta's crust. Clast 1 is the only clast which contains orthorhombic tridymite in our observations. Tridymite is known to have many polymorphs below 400 °C and orthorhombic tridymite is more stable than monoclinic tridymite at 110~400 °C [e.g., 9]. Thus, we consider that clast 1 has experienced a different forming process compared to the other clasts and faster cooling process than at least clasts 2 and 6 below 400 °C.

Table 1. Summary of observation results

	Clast1	Clast2	Clast3	Clast4	Clast5	Clast6
Pyroxene	Mg-Fe zoning	Mg-Fe zoning	Homogeneous	Aug zoning	Mg-Fe zoning	Homogeneous
Silica	Ortho-Trd + Qtz	Qtz	Mono-Trd + Qtz	Qtz	Qtz	Mono-Trd + Qtz
Px-group	A	A	B	C	A	B
Silica-group	(a)	(c)	(b)	(c)	(c)	(b)
Thermal metamorphic degree	Type 4	Type 4	Type 5 or 6	Type 4	Type 4	Type 5 or 6

Aug: Augite, Ortho-Trd: Orthorhombic tridymite, Qtz: Quartz, Mono-Trd: Monoclinic tridymite

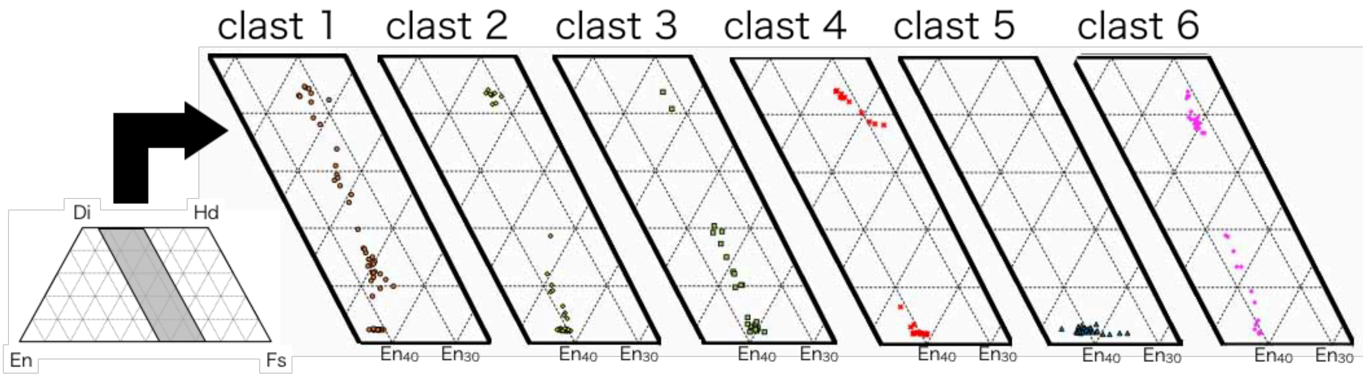

Figure 1. Pyroxene chemical compositions of clasts 1-6 in Camel Donga.

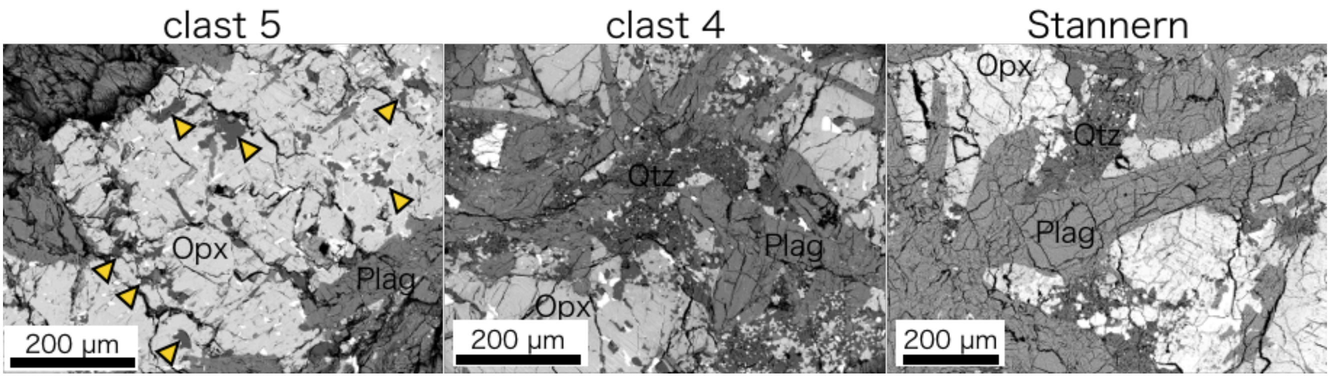

Figure 2. Two types of quartz occurrence in clast 5 and clast 4 and quartz in Stannern (type 4 eucrite) for comparison. Opx: orthopyroxene, Plag: plagioclase, Qtz: quartz. Tiny triangles point quartz in clast 5.

Conclusion: We studied Camel Donga, classified as a monomict brecciated eucrite and considered to be type 5 in thermal metamorphic level. However, we found 6 basaltic clasts with different combinations of silica minerals and thermal metamorphic degrees vary from type 4 to types 5 or 6 as determined from pyroxene compositions and chemical zoning. Therefore, these observations support that Camel Donga is classified as a polymict eucrite as Warren et al. [7] suggested. Most importantly, this study further demonstrates that silica minerals can distinguish whether brecciated eucrites are monomict or polymict by combining with pyroxene chemical compositions.

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