論文の内容の要旨

Crustal evolution of asteroid Vesta as inferred from silica polymorphs in eucrites

(ユークライト隕石中のシリカ多形から読み解く小惑星ベスタ地殻の進化過程)

氏名　　　大野　遼

Eucrites are a basaltic achondrite group and belongs to a HED (Howardite-Eucrite-Diogenite) clan. The HED clan is believed to come from asteroid 4 Vesta (McCord et al., 1970; Consolmagno and Drake, 1977; Binzel and Xu, 1993) and eucrites are considered to have formed in the Vesta's crust. Most eucrites are brecciated and roughly divided into two subgroups, cumulate and non-cumulate eucrites. Cumulate eucrites are inferred to have formed by crystal fractionation from magma ocean and experienced a slow cooling process. Non-cumulate eucrites have experienced various degrees of thermal metamorphism and their thermal metamorphic levels are classified into 6 types based on their textures and mineralogy (Takeda and Graham, 1991). Various reports proposed the causes of thermal metamorphism, for example, burial by lava flow, intrusion, impact or their mixing (Takeda and Graham, 1991; Yamaguchi et al., 2009). However, most mineralogical studies on eucrites have employed only pyroxene and plagioclase, and so their information are limited to high temperatures over 500 °C. Here, I newly focused on silica minerals in eucrites to understand thermal history including a low temperature condition and evolution processes of the eucritic crust.

Silica minerals have many polymorphs (quartz, cristobalite, tridymite, coesite, etc.) including metastable phases under a vast range of temperature and pressure. In particular, tridymite has ~10 polymorphs and its transformation processes are highly complex (Kihara, 2001). In general, two types of tridymite polymorphs are found at room temperature: monoclinic and pseudo-orthorhombic crystal structure. Upon cooling both monoclinic and pseudo-orthorhombic tridymites are reported to transform from hexagonal tridymite via orthorhombic tridymite below 400 °C (Graetsch and Flörke, 1991; Nukui et al., 1978). Thus, silica minerals are considered as good indicators to estimate thermal histories from high temperature to low temperature.

In this study, I have studied silica minerals in 3 cumulate and 9 non-cumulate eucrites. All cumulate eucrites contained monoclinic tridymite, which indicates that monoclinic tridymite formed by a slow cooling process. On the other hand, pseudo-orthorhombic tridymite lamellae were found within monoclinic tridymite in Moama. The finding of the lamellar texture of tridymite is the first report in nature. Furthermore, I showed that the presence of pseudo-orthorhombic tridymite probably required faster cooling than the occurrence of monoclinic tridymite. Therefore, this study concluded that co-existence of monoclinic and pseudo-orthorhombic tridymite was formed by an intermediate cooling rate to allow incomplete transformation of tridymite. However, this result is different from the slower cooling rates of Moama ($\gtrsim$0.0004 °C/yr) than that of Moore County (>0.3 °C/yr, after the shock event) at high temperatures (>500 °C) estimated from compositional profiles of pyroxene exsolution lamellae. The difference of the cooling rates may reflect their geological settings such as formation places with different depths. Y 980433, which contains monoclinic tridymite as silica minerals, cooled slowly at low temperature, as did Moore County. Moore County was finally present at the deep area to obtain a slow cooling rate which allowed crystallization of monoclinic tridymite without excavation to the surface or burial due to debris from other places after excavation. On the other hand, quartz in Y 980433 could be a local product transformed from monoclinic tridymite by a shock event. Therefore, this study proposes that silica minerals in meteorites record thermal histories at low temperatures and shock events.

Monoclinic tridymite is also found in basaltic clasts that are classified into the high metamorphic type (types 5 and 6). On the other hand, cristobalite exists in the low metamorphic type (below type 4) eucrites. The basaltic clast in Camel Donga, which is classified into type 4, does not contain cristobalite but pseudo-orthorhombic tridymite with quartz unlike the other basaltic clasts of type 4. These observations indicate that there is an obvious relationship between thermal metamorphic degrees and assemblage of silica minerals in basaltic clasts of non-cumulate eucrites.

In this study, I performed isothermal heating of eucrite and cooling experiments of eucritic melt to clarify the transformation process of monoclinic tridymite and behavior of silica minerals in eucritic magma, respectively. According to the results of the cooling experiments, cristobalite is an initial silica phase crystallized from eucritic magma and transforms to quartz at the cooling rate between 0.1 and 1 °C/hr. Based on the cooling experiments and observations of non-cumulate eucrites, I suggest that combination of silica minerals varies depending on cooling rates. For example, if the samples are cooled more slowly, the more cristobalite transforms to quartz or tridymite. In other words, the presence of cristobalite and quartz indicates rapider cooling compared with pseudo-orthorhombic and/or monoclinic tridymite. Therefore, I propose that combination of silica minerals is helpful to constrain the cooling rate of basaltic clasts in non-cumulate eucrites in addition to pyroxene thermometer.

Isothermal heating experiments were performed using Yamato (Y) 980433 cumulate eucrite containing monoclinic tridymite as a starting material. The experiments were performed at 500 °C for 168 hrs and 800 °C for 96 hrs. The experiment at 500 °C for 168 hrs indicated that monoclinic tridymite hardly transformed to other phases at low temperature by short time phenomena such as brecciation. Therefore, I suggest that we can use silica minerals to distinguish whether brecciated eucrites are monomict or polymict by combining with pyroxene chemical compositions in basaltic clasts. The experiment at 800 °C for 96 hrs infers that monoclinic tridymite can partly transform to quartz with characteristic cracks. This result indicates that aggregates of monoclinic tridymite and quartz with characteristic cracks in non-cumulate eucrites are formed by partial transformation of monoclinic tridymite to quartz by reheating after the formation of monoclinic tridymite.

From the above results and discussion, it is suggested that basaltic clasts in non-cumulate eucrites have experienced two-stage thermal metamorphism in the eucritic crust. The first metamorphic event was resulted from burial under lava produced by successive eruption, which formed Agoult at the deep crust (Iizuka et al., 2019). This is consistent with my observation in which Agoult contains only monoclinic tridymite indicating a slow cooling process equivalent to cumulate eucrites. The second metamorphic event was caused by igneous intrusions. The intrusions heated the deep eucritic crust and induced transformation from monoclinic tridymite to quartz.