METAMORPHOSED CLASTS IN THE CV CARBONACEOUS CHONDRITE BRECCIAS MOKOIA AND YAMATO 86009: EVIDENCE FOR STRONG THERMAL METAMORPHISM ON THE CV PARENT ASTEROID. K. Jogo, A. N. Krot, and K. Nagashima, Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA. E-mail address: kaori@higp.hawaii.edu

Introduction: CV chondrites are a diverse group of meteorites currently subdivided into three subgroups, oxidized Allende-like (CV_{OxA}), oxidized Bali-like (CV_{OxB}), and reduced (CV_{Red}). These subgroups experienced different degrees of aqueous and/or metasomatic alteration and thermal metamorphism, and may represent different lithologies of a single CV parent asteroid [1]. Neither the size nor the thermal evolution of this asteroid are well-known. Allende is one of the most metamorphosed CV chondrites and appears to have reached peak metamorphic temperature of ~750–850 K [2]. The paleomagnetic records in Allende may imply a partially molten core in CV asteroid [3]. This interpretation, however, has been recently questioned by [4] who suggested that such magnetic records could have been induced by impact. Here, we describe the mineralogy, petrography, and O-isotope compositions of heavily-metamorphosed clasts in the CV chondrite breccias Mokoia and Yamato-86009 (Y-86009), which appear be genetically related to CV chondrites [e.g., 5, 6], and, therefore, provide important constraints on the the internal structure and thermal history of the CV parent asteroid.

Mineralogy and the O-isotope compositions of the clasts: The metamorphosed clasts in Mokoia and Y-86009 are coarse-grained, granular, polymineralic rocks composed of Ca-rich (up to 0.6 wt% CaO) ferroan olivine ($Fa_{34–39}$), ferroan Al-diopside ($Fs_{9–13}Wo_{47–50}$, ~2−7 wt% Al_2O_3), plagioclase ($An_{37–84}Ab_{63–17}$), Cr-spinel [Cr/(Cr+Al) = 0.19−0.45, Fe/(Fe+Mg) = 0.60−0.79], nepheline, pyrrhotite, pentlandite, Ca-phosphate, and rare grains of Ni-rich taenite; low-Ca pyroxene is absent. Most clasts have triple junctions between silicate grains, indicative of prolonged thermal annealing. Based on the olivine-spinel [7] and high-Ca pyroxene thermometry [8], the estimated metamorphic temperature recorded by the clasts is $\geq$1100 K.

On a three-isotope oxygen diagram (Fig. 1), the compositions of olivine in the clasts plot below the terrestrial fractionation (TF) line ($\Delta^{17}O$ ranges from −3.3‰ to −5.4‰, 2σ ~ 1‰), along or near carbonaceous chondrite anhydrous mineral (CCAM) line and the Allende mass fractionation (AMF) line [9].

Comparison of clasts with known groups of chondrites and achondrites: The equilibrated textures of clasts are also found in ordinary and carbonaceous chondrites of high petrologic types (e.g., type 5−6 of H, L, LL, R, CK), CV metachondrites (possibly formed by the annealing of CV chondrites [10]), primitive and differentiated achondrites. However, a genetic relationship between the clasts and these meteorites is unlikely for following several reasons:

(*i*) The averaged bulk chemical compositions of the clasts obtained by defocused-beam EPMA show that compatible and plagiophile elements (e.g., Al, Na, K) are not as heavily depleted as in achondrites [11], and are similar to those in chondrites and primitive achondrites.

(*ii*) The absence of low-Ca pyroxene in the clasts is inconsistent with mineralogy of the metamorphosed chondrites, CV metachondrites and primitive achondrites [11]. Although brachinites contain high-Ca pyroxene and no or rare low-Ca pyroxene [12], they are much coarser grained (up to ~1 mm in size) than the clasts (up to ~50 μm in size), and have distinctly different O-isotope compositions [13] (Fig. 1).

(*iii*) Chemical compositions of olivine grains in the clasts ($Fa_{34–39}$) and their O-isotope compositions (below the TF line) are inconsistent with those in equilibrated ordinary chondrites ($Fa_{16–32}$; $\Delta^{17}O > 0$; [11]) and in CV metachondrites ($Fa_{\sim 22}$; [14]). There are also differences in chemical compositions of spinel grains between the clasts and ordinary chondrites: Cr/(Cr+Al) = 0.19−0.45 *vs.* 0.85−0.95, respectively [15].

(*iv*) Although the Fa contents, Cr/(Cr+Al) ratio in spinel and O-isotope compositions of olivine grains in the clasts overlap with those in CK chondrites [11,16,17], the latter contain higher NiO contents (<0.3 *vs.* 0.3−0.7 wt%) [16]. In addition, plagioclase in clasts does not show bimodal distribution of An contents as observed in CK plagioclase [16]. The clasts also lack magnetite, which are rather common in CK chondrites [11].

Formation of the clasts by metamorphism of the CV-like chondritic precursors: A few clasts, which experienced metamorphism to a lower degree, have O-isotope heterogeneity (Fig. 1) and chondrule-like textures; some of them are surrounded by finer-grained mantle mineralogically similar to the enclosed objects. The re-crystallized texture of the mantle suggests that it formed by annealing of fine-grained materials. Based on high-Ca pyroxene thermometry [8], the estimated metamorphic temperature recorded by the mantle is $\geq$1100. The bulk chemical compositions and/or texture of the mantle are similar to those of the Allende matrix and coarse-grained igneous rims around Allende chondrules [18]. Thus, the clasts could have formed by prolonged thermal metamoprhism of the CV-like materials.

The absence of low-Ca pyroxene in the Mokoia and Y-86009 clasts may suggest that low-Ca pyroxene was replaced during the thermal metamoprhism. We note that in the CV_{OxA} chondrites and Allende dark inclusions, low-Ca pyroxene is commonly preferentially replaced by ferroan olivine [19]. These observations may suggest that the precursor materials of the clasts were heavily-altered CV chondrites. This hypothesis is supported by several similarities between the clasts and CV_{OxA}: (*i*) Al- and Ca-rich bulk chemical compositions of clasts and CV_{OxA} chondrites and Allende dark inclusions [20]. (*ii*)

The similar textures and bulk chemical compositions of the mantle in less-metamorphosed clast to those of coarse-grained igneous rims around Allende chondrules [18]. (*iii*) O-isotope compositions of olivine in metamorphosed clasts overlapping with those in Allende [21] (Fig. 1). (*iv*) Similar sizes of chondrule-like objects in the less-metamorphosed clasts (0.2−1 mm in diameter) and CV chondrules (0.09−2.5 mm in diameter [22]).

Alteration of the clasts prior to metamorphism: In most cases, O-isotope compositions of olivine grains within an individual clast are uniform, suggesting that their O-isotope compositions could have been homogenized during thermal metamorphism [6]. There are, however, variations in O-isotope compositions (mainly in $\delta^{18}O$) among the clasts (Fig. 1). E.g., the difference in $\delta^{18}O$ values of Y86#1 and M25#2 clasts is up to ~10‰.

Such $\delta^{18}O$ differences suggest that each clast's precursor had either different O-isotope compositions, or that O-isotopes of precursors were once homogenized and then mass-dependently re-distributed at different temperature during thermal metamorphism. Under the metamorphic temperature of clasts of 1100 K < T < 1570 K (1570 K is a melting point of the Fo-Di-An system [23]), expected $\delta^{18}O$ fractionation values in pyroxene and plagioclase relative to olivine are small as <1‰ and <3‰, respectively [24]. If we assume that O-isotope composition of each clast's precursor is between these major three minerals, possible ranges of O-isotope compositions of each clast's precursor are inconsistent. Therefore, precursor of each clast could have had different O-isotope compositions.

The observed spread in $\delta^{18}O$ values between the clasts may reflect various degrees of aqueous/metasomatic alteration they experienced prior to thermal metamorphism. Oxygen-isotope composition of water ice (most likely source of water) that accreted into CV chondrite parent asteroid appears to have had higher $\Delta^{17}O$ value than anhydrous silicates [21,25−27]. As a result of O-isotope exchange between aqueous solution and anhydrous silicates, the former evolved towards lower $\Delta^{17}O$ values. Aqueously produced minerals in CV chondrites (e.g., fayalite, magnetite, Ca,Fe-rich pyroxenes, andradite) appear to have recorded this fluid-rock interaction. On a three-isotope oxygen diagram, their compositions plot along mass-dependent fractionation line with $\Delta^{17}O \sim -3$‰ [21,25−27], close to the AMF line. The observed spread in $\delta^{18}O$ values between the aqueosly produced minerals is up to 20‰. We suggest that the precursor materials of the Mokoia and Y-86009 experienced various degrees of aqueous alteration prior to metamorphism. For example, the precursor materials of clast Y86#1 with the highest $\delta^{17}O$ and $\delta^{18}O$ values may have experienced stronger degree of aqueous alteration and contain larger volumes of altered minerals compared to those of other clasts.

Implications for early accretion of the CV asteroid: Wakita et al. [28] performed numerical calculations of thermal evolution of a CV-like asteroid with various initial parameters (accretion time, size, and water/rock mass ratio). In order to reach 1100 K, which is the lower limit of metamorphic temperature experienced by the clasts, the CV asteroid with >50 km radius should accrete not later than ~2 Myr after formation of CAIs with the canonical $^{26}Al/^{27}Al$ ratio of 5×10^{-5}, consistent with Al-Mg ages of CV chondrules of ~ 1.5 Myr after CV CAIs [29].

Conclusions: We conclude that the Mokoia and Y-86009 clasts formed by thermal metamorphism of heavily-altered chondrites on the CV parent asteroid, which must have accreted within 2 Myr after CAI formation and experienced thermal metamorphism $\geq$ 1100 K. The presence of heavily-metamorphosed clasts and the lack of igneous clasts in CV chondrite breccias argue against the existence of a metal core on the CV parent asteroid.

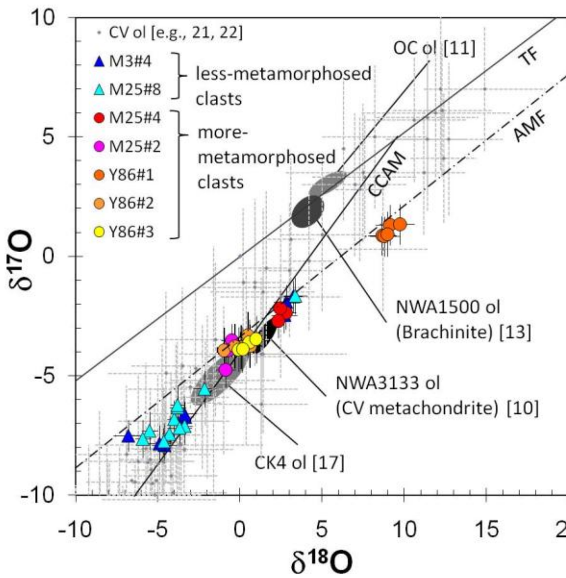

Fig. 1. O-isotope compositioins of olivine in Mokoia (M) and Y-86009 (Y) clasts which experienced different degrees of metamorphism. Errors are 2σ.

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