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

Introduction: CV chondrites are a highly diverse group of meteorites currently subdivided into three subgroups (oxidized Allende-like, oxidized Bali-like, and reduced) which experienced different degrees of aqueous and/or iron-alkali-halogen 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. Based on the unidirectional remanent magnetization of the Allende meteorite, it has been proposed that the CV asteroid could have experienced melting, igneous differentiation and core formation [2]. However, no CV chondrites more heavily metamorphosed than Allende, that appears to have experienced peak metamorphic temperature of ~750–850K [3–5], are currently known. The CV chondrite breccias Mokoia and Yamato-86009 contain heavily-metamorphosed clasts, which could be genetically related to CV chondrites [6,7]. If this is the case, these clasts may provide an evidence for strong thermal metamorphism or even partial melting on the CV parent asteroid.

The metamorphosed clasts in Mokoia and Y-86009 are coarse-grained, granular, polymineralic rocks composed of ferroan olivine, ferroan diopside, anorthitic plagioclase, Cr-spinel, nepheline, sulfides, and rare grains of Ni-rich taenite; low-Ca pyroxene is absent [6–11]. Some clasts exhibit triple junctions between silicate grains, indicative of prolonged annealing at high temperature. The peak metamorphic temperature estimated for the Mokoia clasts are $\geq$970–1170K [6,7]. Although both nebular and asteroidal origins of clasts were proposed [6, 8], the preservation of chondrule textures and the presence of re-crystallized finer-grained material around them suggest the clasts formed by annealing of chondrules and matrices on a chondrite parent asteroid [7]. The mineralogy and bulk chemical compositions of the clasts, however, are inconsistent with known groups of thermally metamorphosed chondrites [6, 7, 10, 11]. O-isotope compositions of the only clast from Y-86009 measured so far [10] are similar to those of CV chondrites, supporting its genetic relationship to CV chondrites [6]. To further test this hypothesis, we measured O-isotopic compositions of olivine grains in four heavily-metamorphosed clasts from Mokoia.

Analytical technique: O-isotope compositions were analyzed with the UH Cameca ims-1280 ion microprobe in multicollection mode: $^{16}O^-$, $^{17}O^-$ and $^{18}O^-$ were measured simultaneously using multicollection Faraday cup (FC), monocollection electron multiplier and multicollection FC, respectively, described in detail elsewhere [12].

Results and Discussion: The Mokoia clasts *M25#2* (Fig. 1a) and *M25#4* have equilibrated textures with triple junctions between olivine, pyroxene and plagioclase grains, and uniform chemical compositions of olivine and pyroxene. Two other clasts, *M3#4* (Fig. 1b) and *M25#8* (Fig. 1c), have unequilibrated textures. The clast *M3#4* has a porphyritic texture and shows some variations in chemical compositions of pyroxene ($En_{38-41}Wo_{50-51}$). The clast *M25#8* has a coarse-grained porphyritic texture and is surrounded by a finer-grained rim [see 7 for details]. The largest olivine phenocryst shows Fe-Mg zoning (Fa_{25-30}).

Oxygen-isotope compositions of olivine in the Mokoia clasts are similar to those in the Y-86009 clast reported by [7] and plot along carbonaceous chondrite anhydrous mineral (CCAM) line (Fig. 2).

Oxygen-isotope compositions of olivine in clasts with equilibrated textures are uniform; the $\Delta^{17}O$ values are similar within uncertainty of our measurements (Fig. 2). These compositions may represent the original compositions of precursor materials or they could have been modified by O-self diffusion during thermal metamorphism. Based on olivine-spinel and high-Ca pyroxene thermometers, these clasts were metamorphosed at $\geq$970–1170K [7]. Because no chemical zoning is observed in 50-μm-sized olivine grains of the clasts, these grains were probably chemically homogenized during thermal metamorphism. Based on Fe-Mg diffusion coefficient in olivine at 1000K, $\sim10^{-20}$ m^2/s [13], thermal metamorphism at 1000K for at least 2000 yrs is required to complete Fe-Mg exchange in a 50-μm-sized olivine grain. Using O-self diffusion coefficients at 1000K ($\sim1\times10^{-22}$ m^2/s [14] and $\sim3\times10^{-24}$ [15], the estimated diffusion distances of oxygen in olivine during this time are ~7 and ~1 μm, respectively. Because these values are obtained using the minimum temperature and duration of thermal metamorphism recorded by the clasts, they provide a lower limit of the oxygen diffusion distance. We infer that the narrow range in O-isotope compositions of the clasts with equilibrated textures could be due to O-isotope equilibration during thermal metamorphism.

On a three-isotope oxygen diagram (Fig. 2a), compositions of clasts with unequilibrated textures show a bi-modal distribution. In both clasts, O-isotope compositions of the adjacent olivine grains are variable, implying that the clasts appear to have escaped O-isotope equilibration during thermal metamorphism and may have preserved the original compositions of precursor materials. The observed range of O-isotope compositions of the Mokoia clasts overlaps with compositions of chondrules from CV chondrites [16–18].

We conclude that O-isotope compositions of the heavily-metamorphosed clasts from Mokoia and Y-86009 are consistent with their origin on the CV chondrite parent asteroid [6, 7]. The absence of low-Ca pyroxene in the clasts could be due to its preferential replacement by ferroan olivine, as commonly observed in chondrules from the Allende-like oxidized CV chondrites and Allende dark inclusions [19, 20]. Thus, the Mokoia and Y-86009 metamorphosed clasts could have formed by annealing of heavily altered CV chondritic material.

References: [1] Krot A. N. et al. (1995) *Meteoritics, 30*, 748–775. [2] Weiss B. P. et al. (2010) *LPS 41*, Abstract #1688. [3] Bonal L. et al. (2006) *GCA, 70*, 1849–1863. [4] Brearley A. J. (1997) *Science, 276*, 1103–1105. [5] Brearley A. J. (1999) *Science, 285*, 1380–1382. [6] Krot A. N. and Hutcheon I. D. (1997) *LPS 28*, Abstract #2347. [7] Jogo K. and Krot A. N. (2010) *MAPS, 73*, A5073. [8] Cohen R. E. et al. (1983) *GCA*, 47, 1739–1757. [9] Krot A. N. et al. (1998) *MAPS*, *33*, 1065–1085. [10] Jogo K. et al. (2008) *LPS 39*, Abstract #1576. [11] Jogo K. and Nakamura T. (2009) *MAPS, 72*, A51. [12] Makide K. et al. (2009) *GCA*, 73, 5018-5050. [13] Chakraborty S. (1997) *JGR*, *102*, 12317-12331. [14] Gérand O. and Jaoul O. (1989) *JGR*, *94*, 4119–4128. [15] Ryerson F. J. et al. (1989) *JGR*, 94, 4105-4118. [16] Chaussidon M. et al. (2008) *GCA, 72*, 1924–1938. [17] Jones R. H. et al. (2004) *GCA*, *68*, 3423–3438. [18] Rubin A. E. et al. (1990) *EPSL*, *96*, 247–255. [19] Krot A. N. et al. (2004) *Antarctic Meteorite Res.*, *17*, 154–172. [20] Brearley A. J. and Krot A. N. (2010) in *Metasomatism and Metamorphism: The Role of Fluids in Crustal and Upper Mantle Processes*, eds. D. E. Harlov and H. Austrheim, submitted.

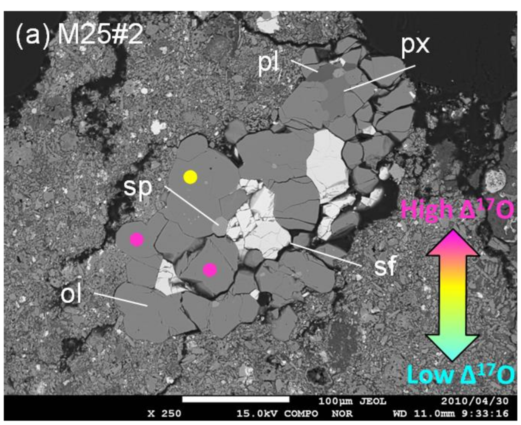
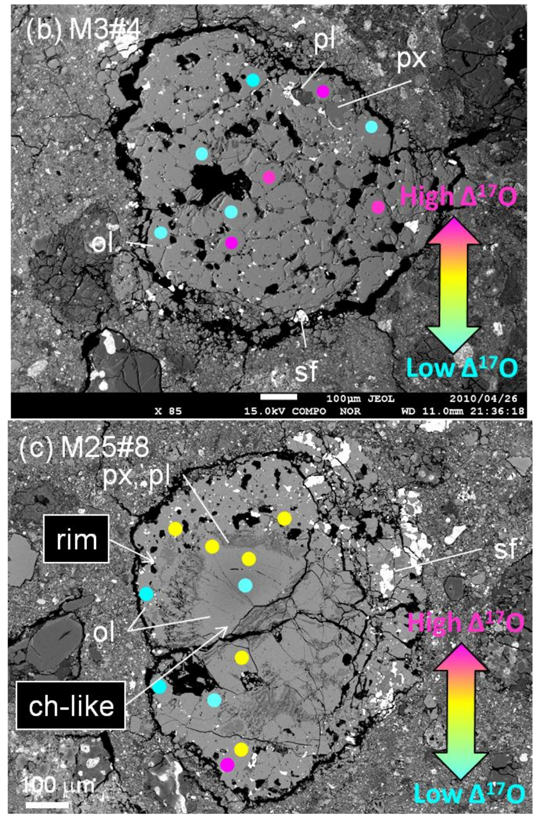


Fig. 1. BSE images of the Mokoia clasts with equilibrated (a) and unequilibrated (b, c) textures. Circles show SIMS measurement spots in olivine; color of the spots represents $\Delta^{17}O$ values as shown in Fig. 2b. ol: olivine; px: pyroxene; pl: plagioclase; sp: spinel; sf: sulfide; rim: igneous rim; ch-like: chondrule-like portion.



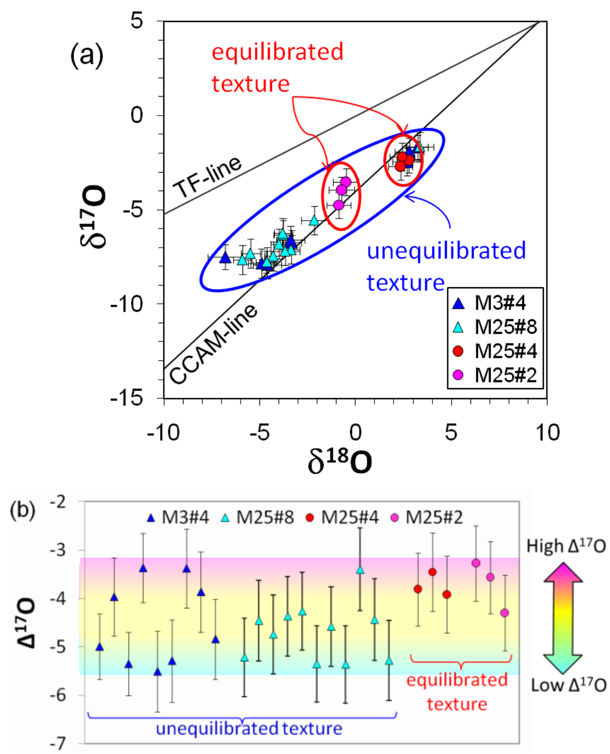


Fig. 2. Three O-isotope diagram (a) and $\Delta^{17}O$ values (b) of olivine in the heavily-metamorphosed Mokoia clasts with equilibrated and unequilibrated textures. Errors are 2σ.