

MULTIPLE CV CHONDRULE PRECURSORS ORIGINATING FROM THE INNER AND OUTER SOLAR SYSTEM: EVIDENCE FROM CR-TI-O ISOTOPE SYSTEMATICS OF ALLENDE CHONDRULES.

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Introduction: Understanding the material transport and mixing processes in the protoplanetary disk is crucial to constrain the early disk dynamics. Recent Cr-Ti-O isotope analyses of individual chondrules from carbonaceous chondrites (CCs) demonstrated that CC chondrules have isotopic characteristics of both inner and outer disk reservoirs, indicating large-scale outward transport of materials that originated from the inner (i.e., non-carbonaceous: NC) disk reservoir [1]. In contrast, chondrules from NC and CC meteorites investigated [2, 3] exhibit distinct Cr-Ti-O isotopic characteristics, suggesting a limited mixing of the inner and outer Solar System materials. These observations indicate that (i) chondrule formation occurred at both reservoirs, and (ii) a small fraction of chondrules originating from the NC reservoir migrated into the CC reservoir. To better understand the nature of disk transport in the early Solar System, we further conducted Cr-Ti-O isotope analyses of individual chondrules extracted from the Allende (CV) chondrite.

Sample preparation and analytical procedures: We made 20 thick sections (~0.5mm thickness) of the Allende and searched chondrules larger than ~1.5 mm in diameter, which allow precise Cr and Ti isotope analyses of individual chondrules. Five chondrules [2 barred olivine (BO; AL1, AL2), 1 Al-rich (AL3), 1 pyroxene-rich (AL4), 1 PO (AL5)] were selected for chemical and isotopic analyses. Mg#s [Mg/(Mg+Fe) molar %] of olivine and pyroxene in the 5 chondrules were examined with a Hitachi S-3400 SEM-EDS.

Oxygen three-isotope analyses of the 5 chondrules were performed with a Cameca IMS 1280 SIMS at the UW-Madison. The analytical conditions are similar to those described in [4]. A ~12 μm diameter (2 nA) ¹³³Cs⁺ primary ion beam was used for analyses. Secondary oxygen ions (¹⁶O⁻, ¹⁷O⁻, ¹⁸O⁻) were detected simultaneously using multi-collector Faraday cups. The external reproducibility of the running standard was 0.2‰ for δ¹⁸O and 0.3‰ for δ¹⁷O and Δ¹⁷O (2SD).

After the SIMS analyses, 3 out of the 5 chondrules (AL1, AL2, AL3) were extracted from the thick sections using a diamond drill equipped with a micro-mill [5] at the Alaska Fishery Science Center, National Oceanic and Atmospheric Administration. Chemical separation of Cr and Ti of the 3 chondrules was

conducted following a sequential separation procedure [6]. Chromium and Ti isotope ratios were determined using Thermo Fisher Scientific TRITON Plus TIMS and Neptune Plus MC-ICP-MS at Japan Agency for Marine-Earth Science Technology, respectively. The detailed procedures for Cr and Ti isotope analyses were described in [6]. The data are reported in ε⁵⁰Ti and ε⁵⁴Cr values as the parts-per-10,000 deviation from the value measured for the NIST 3162a Ti and NIST 979 Cr standard solutions, respectively.

Results: Mg#s of olivine in chondrules studied tend to be lower than those of coexisting pyroxene, suggesting Mg-Fe diffusion in olivine during thermal metamorphism on the CV parent body [e.g., 7]. Hence, only pyroxene values were used to determine the mean Mg#s of each chondrule. All 5 chondrules studied are Mg-rich (Mg# > 90). Of those, 4 chondrules, except for chondrule AL5 (Mg# = 93), have Mg# > 97.

Five chondrules studied here do not have typical O-isotope ratios of Mg-rich chondrules in CV chondrites with Δ¹⁷O from -6‰ to -4‰ and peak at ~-5.5‰ [7]. Three out of the 5 chondrules (AL1, AL4, AL5) show internally homogeneous O-isotope ratios. The mean Δ¹⁷O values (± 2σ) of the 3 chondrules are -4.10 ± 0.20‰ (AL1), -3.65 ± 0.15‰ (AL4), and -0.01 ± 0.19‰ (AL5). The other two chondrules (AL2, AL3) show O-isotope heterogeneity among coexisting minerals. Oxygen isotope ratios of olivine in chondrule AL2 are homogeneous (Δ¹⁷O = -0.09 ± 0.24; 2SD), which are systematically ¹⁶O-depleted compared to those of coexisting pyroxene (Δ¹⁷O = -4.60 ± 0.28; 2SD). The other chondrule AL3 that consists of plagioclase, Al-Ti-rich pyroxene, olivine, and spinel, shows a large heterogeneity in Δ¹⁷O ranging from -23.9 to -2.2‰. Spinel and plagioclase are the most ¹⁶O-rich (Δ¹⁷O ≤ -20.9) and ¹⁶O-depleted (Δ¹⁷O ≥ -2.6) among coexisting minerals, respectively. Δ¹⁷O values of Al-Ti-rich pyroxene and olivine are intermediate (-10.8 ≤ Δ¹⁷O ≤ -8.2).

The ε⁵⁴Cr values of 3 chondrules (AL1, AL2, AL3) exhibit only limited variation ranging from 0.6 ± 0.1 to 1.1 ± 0.1 (2σ), which are within the range of bulk CC meteorites. In contrast, their ε⁵⁰Ti values are more variable (-1.0 ± 0.4 to 4.0 ± 0.3; 2σ) including NC-like negative ε⁵⁰Ti value from AL2.

Discussion: The existence of ^{16}O -rich spinel in Al-rich chondrule AL3 (Mg# = 99) suggests that a part of the chondrule precursor is Ca-Al-rich inclusions (CAIs) or amoeboid olivine aggregates (AOAs). The mean $\Delta^{17}\text{O}$ value calculated from olivine and pyroxene data is depleted in ^{16}O ($-9.4 \pm 1.7\%$; 2SD) compared to coexisting spinel, indicating that this chondrule formed by melting of a mixture of ^{16}O -rich CAI or AOA-like and ^{16}O -depleted precursors [e.g., 8, 9]. As for the previous studies [1, 2], we calculated two-component mixing lines (Fig. 1) to assess possible precursor materials. The Cr-Ti-O systematics of chondrule AL3 can be explained by a mixing between forsterite-rich AOA and NC-like endmembers (Fig. 1).

The BO chondrule AL1 (Mg# = 98) exhibits Cr-Ti-O isotopic compositions similar to those of bulk CC meteorites, indicating its formation in the CC reservoir. The Cr-Ti-O systematics of this chondrule is broadly consistent with its formation by melting of a mixture of AOA-like and NC-like endmembers (Fig. 1).

Another BO chondrule AL2 (Mg# = 98) exhibits unique Cr-Ti-O isotope systematics. This chondrule consists mostly of olivine that are systematically ^{16}O -depleted ($\Delta^{17}\text{O} \sim 0\%$) compared to typical Mg-rich (Mg# > 90) chondrules from CV chondrites ($\Delta^{17}\text{O} = \sim -5\%$; e.g., [7-9]). The ^{16}O -depleted signature is rather consistent with an O-isotope characteristic of the NC reservoir [e.g., 10, 11]. Moreover, this chondrule has negative $\varepsilon^{50}\text{Ti}$, supporting its relation to the NC reservoir. In contrast, the $\varepsilon^{54}\text{Cr}$ value of this chondrule is within the range of the CC meteorites (Figs. 1a, b), which is inconsistent with its formation in the NC reservoir. As mentioned earlier, pyroxene grains in the periphery of this chondrule show more ^{16}O -rich signature (Figs. 1b, c) that is similar to typical CV chondrules. The positive $\varepsilon^{54}\text{Cr}$ value and O-isotope disequilibrium between olivine and pyroxene suggest that the final-chondrule melting that produced pyroxene occurred in the CC reservoir, but olivine grains resisted complete melting (i.e., O-isotopic relict). If correct, one of the precursors of this chondrule would have formed in the NC reservoir. The precursor was subsequently transported into the outer Solar System and experienced final melting in the CC reservoir to produce chondrule AL2.

Summary: The large ranges of Cr-Ti-O isotope ratios among CV chondrules indicate that they formed by reprocessing of multiple chemically and isotopically distinct precursors that include the materials originating from the inner Solar System.

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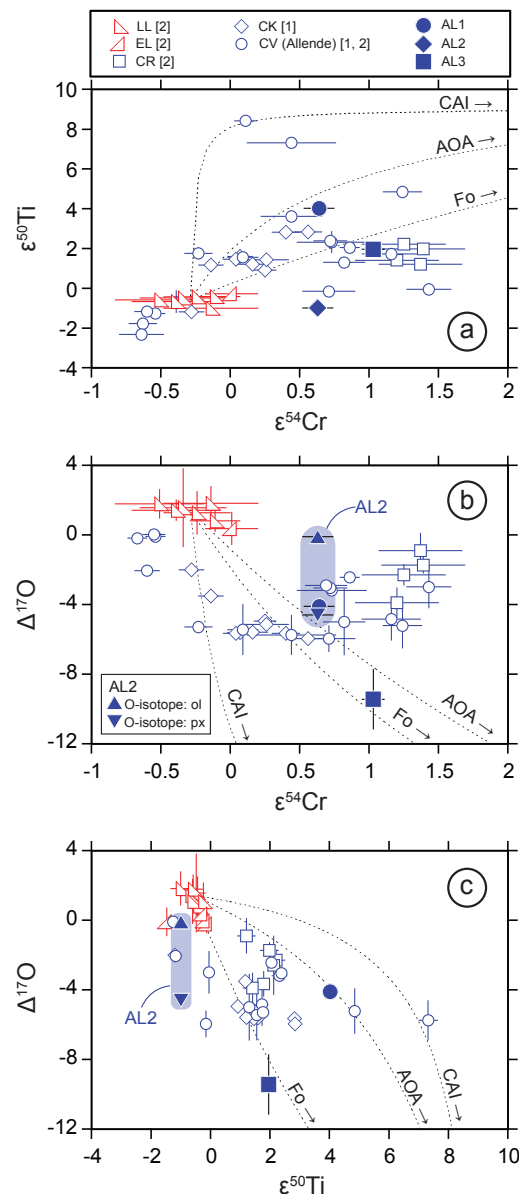


Fig. 1. (a) $\varepsilon^{50}\text{Ti}$ - $\varepsilon^{54}\text{Cr}$, (b) $\Delta^{17}\text{O}$ - $\varepsilon^{54}\text{Cr}$, and (c) $\Delta^{17}\text{O}$ - $\varepsilon^{50}\text{Ti}$ plots for individual chondrules. Literature data are shown in open symbols for comparison [1, 2]. Dashed curves represent two-component mixing between a NC-like component and three different endmembers; CAI-like dust (CAI), AOA-like dust (AOA), forsterite-rich AOA-like dust (Fo).