OXYGEN ISOTOPIC COMPOSITIONS OF THE ALLENDE TYPE C CAIS: EVIDENCE FOR ISOTOPIC EXCHANGE DURING NEBULAR MELTING AND ASTEROIDAL THERMAL METAMORPHISM.

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Introduction: Most CAIs in primitive chondrites (e.g., CR2, CO3.0) have uniformly ^{16}O-rich compositions ($\Delta^{17}O \leq -20$‰) and large ^{26}Mg* indicating early formation in an ^{16}O-rich gaseous reservoir [1,2]. Few CAIs in these meteorites subsequently experienced melting and isotopic exchange in the presence of an ^{16}O-poor nebular gas [3-5]. In contrast, most CV CAIs, which appear to have formed very early, during a short time interval [6,7], show large O-isotopic heterogeneity: melilite and anorthite are typically ^{16}O-depleted ($\Delta^{17}O > -10$‰) compared to spinel and Al,Ti-diopside, which largely retain their original ^{16}O-rich compositions [8]. Because some melilite and anorthite in CV CAIs have ^{16}O-rich compositions, isotopic exchange with an ^{16}O-poor external reservoir is required. In addition, most isotopically heterogeneous CV CAIs are surrounded by multilayered rims with the outermost layers of Al-diopside and forsterite being ^{16}O-rich. Since these rims are resulted from high-temperature gas-solid or gas-melt interaction, the final stages of CAI formation must have occurred in the presence of an ^{16}O-rich nebular gas.

Several mechanisms have been proposed to explain the nature of this selective isotopic exchange, but all have some problems. (*i*) High-temperature gas-solid exchange in the solar nebula is inconsistent with the measured oxygen self-diffusion rates in melilite, anorthite, diopside, and spinel [9,10]. (*ii*) Isotopic exchange between the ^{16}O-rich CAI melt and an ^{16}O-poor nebular gas either during CAI melting or crystallization is difficult to reconcile with the inferred crystallization sequence of CAI melts [11]. (*iii*) Isotopic exchange during disequilibrium melting [12,13] may avoid these problems, but has yet to be reproduced experimentally. If O-isotopic heterogeneity of CV CAIs resulted from gas-melt isotopic exchange in the solar nebula, rapid fluctuations of O-isotopic compositions of the nebular gas (from ^{16}O-rich to ^{16}O-poor to ^{16}O-rich again) are required [12,14]. In order to understand the role of melting and asteroidal processing in O-isotopic exchange, we measured O-isotopic compositions of six coarse-grained, igneous, anorthite-rich (Type C) CAIs (*100*, *160*, *6-1-72*, *ABC*, *TS26*, and *93*) from Allende previously characterized by [15-18].

Results: CAIs *ABC* and *TS26* contain relict chondrule fragments composed of forsteritic olivine and low-Ca pyroxene; CAI *93* is overgrown by a coarse-grained igneous rim of pigeonite, augite, and anorthitic plagioclase. These three CAIs contain Na-rich åkermanitic melilite (0.4-0.6 wt% Na_2O; $Åk_{63-74}$) and Cr-bearing Al,Ti-diopside (up to 1.6 wt% Cr_2O_3, 1-23 wt% Al_2O, and 0.5-7 wt% TiO_2).

CAIs *100*, *160*, and *6-1-72* consist of Al,Ti-diopside, Na-bearing åkermanitic melilite (0.1-0.4 wt% Na_2O; $Åk_{30-75}$), spinel, and fine-grained anorthite. Most Al,Ti-diopside and melilite grains have "lacy" textures (containing abundant rounded or prismatic inclusions of anorthite). Melilite-anorthite grains are pseudomorphed to varying degrees by grossular, monticellite, ±forsterite, ±wollastonite. CAI *6-1-72* contains a relict Type B CAI-like portion composed of gehlenitic melilite ($Åk_{10-40}$), Al,Ti-diopside, spinel, anorthite, perovskite, and PGE nuggets, overgrown by lacy melilite and Al,Ti-diopside. Some melilite and Al,Ti-diopside in CAIs *100* and *160* are texturally similar to those in the Type B portion of *6-1-72*. Melilite and anorthite in the CAI peripheries are replaced by nepheline and sodalite crosscut by andradite-bearing veins.

We infer that CAIs *100*, *160*, and *6-1-72* formed by melting of coarse-grained Type B-like CAIs. The precursor CAIs either experienced extensive replacement of melilite and spinel by anorthite and diopside, or gained silica and sodium during the melting event. CAIs *ABC*, *93*, and *TS-26* experienced melting in the chondrule-forming regions with addition of ferromagnesian silicates (olivine, low-Ca pyroxene, and high-Ca pyroxene). The CAIs experienced thermal metamorphism resulting in pseudomorphic replacement of melilite and anorthite by grossular, monticellite, forsterite or wollastonite, followed by iron-alkali metasomatic alteration and formation of nepheline, sodalite, Ca-Fe-rich pyroxenes, wollastonite, and andradite.

Oxygen isotopic compositions were measured with the Nancy and Hokkaido University Cameca ims 1270 and Hawai'i Cameca ims 1280 ion microprobes in multicollection mode using FC-FC-FC or FC-EM-FC for ^{16}O, ^{17}O, and ^{18}O, respectively, and in monocollection mode using EM, and by SCAPS; for details see [19-21].

Coarse-grained anorthite and Al,Ti-diopside in the Type C CAIs associated with chondrule material (*ABC*, *93*, *TS26*) are ^{16}O-depleted compared to finer-grained anorthite and lacy Al,Ti-diopside in *100* and *160* (Figs. 1a-e), indicating that only diopside in *ABC*, *TS26*, and *93* experienced isotopic exchange during melting in the presence of ^{16}O-poor nebular gas. Al,Ti-diopside in the Type B and C portions of *6-1-72* are also ^{16}O-depleted relative to Al,Ti-diopside in *100* and *160*, suggesting isotopic exchange during melting. Melilite in five CAIs is ^{16}O-poor: in *100, 160*, and *6-1-72*, melilite is typically more ^{16}O-depleted than anorthite. Grossular, monticellite, and forsterite replacing lacy melilite in *100* are similarly ^{16}O-depleted (not shown in Fig. 1c), whereas grossular in *160* is ^{16}O-enriched relative to melilite. Since the pseudomorphic replacement of lacy melilite by grossular, monticellite, and forsterite occurred during late-stage metamorphism [17,18,21,22], we infer that at least some of the O-isotopic exchange of melilite and anorthite in Type C CAIs continued after formation of grossular, probably during fluid-assisted thermal metamorphism. Similar processes may have affected melilite in the CO CAIs [23]. If correct, melilite and anorthite(?) grains in many CAIs from the least metamorphosed CV chondrites are expected to be ^{16}O-enriched relative to typical (^{16}O-depleted) melilite grains from the Allende CAIs. The common presence of ^{16}O-rich ($\Delta^{17}O$ up to -25‰) melilite in Type A CAIs from the CV3.1 Kaba [24,25] supports this conclusion.

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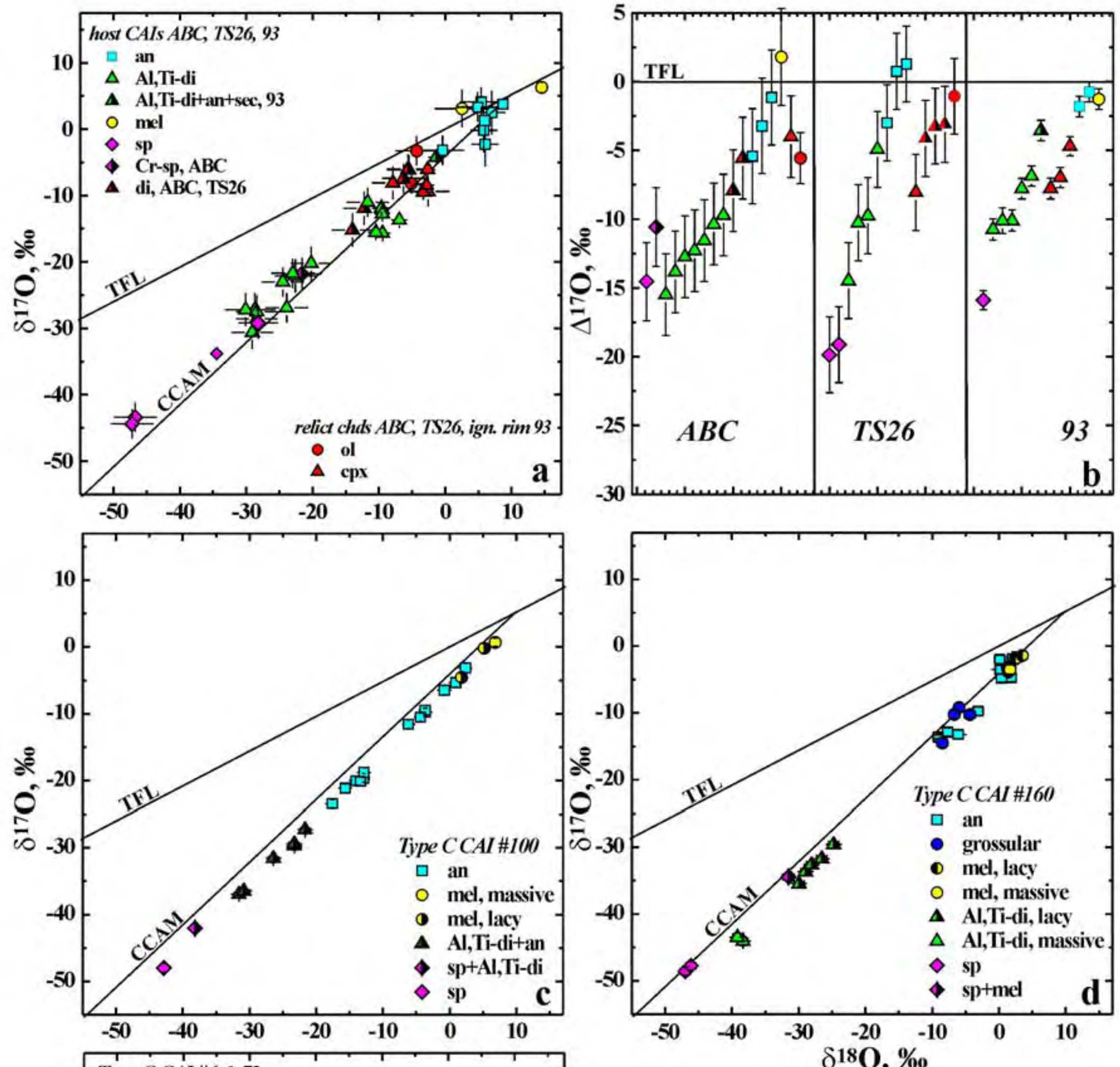

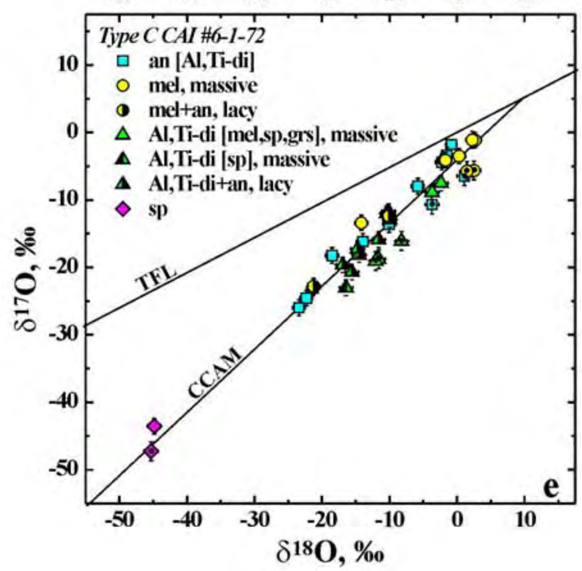

Fig. 1. Oxygen isotopic compositions of the Allende Type C CAIs. CAIs *TS26*, *ABC*, and *93* were melted in the chondrule-forming region; CAIs *100* and *160* show no evidence for being affected by melting in this region; their fine-grained anorthite and lacy Al,Ti-diopside are ^{16}O-enriched compared to coarse grained anorthite and Al,Ti-diopside in *TS26*, *ABC*, and *93*. Both massive and lacy Al,Ti-diopside of a Type B and Type C portions of *6-1-72* are ^{16}O-depleted relative to those in *100* and *160*, possibly due to early melting. Melilite grains in all six CAIs are similarly ^{16}O-depleted and may have experienced additional isotopic exchange during fluid-assisted thermal metamorphism. Points with black dots in "e" indicate compositions acquired at UH; other spots for this CAI are from CNRS/CRPG. an = anorthite; cpx = augite; Al,Ti-di = Al,Ti-diopside; grs = grossular; mel = meliλιτε; πξ = λοω–Χα πψροξενε. Ερρορσ αρε 2σ. TFL = terrestrial fractionation line; CCAM = carbonaceous chondrite anhydrous mineral line.