

OXYGEN ISOTOPE COMPOSITIONS OF THE KAUDUN METEORITE – INDICATIONS FOR AQUEOUS ALTERATION OF E-CHONDRITES.

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Introduction: The Kaidun microbreccia is a unique meteorite due to the diversity of its constituent clasts. Fragments of various types of carbonaceous (CI, CM, CV, CR), enstatite (EH, EL), and ordinary chondrites, basaltic achondrites, and impact melt products have been described, and also several unknown clasts [1, and references therein]. The small mm-sized clasts represent material from different places and times in the early solar system, involving a large variety of parent bodies [2]; meteorites are of key importance to the study of the origin and evolution of the solar system, and Kaidun is a collection of a range of bodies evidently representing samples from across the asteroid belt. The parent-body on which Kaidun was assembled is believed to be a C-type asteroid, and 1-Ceres and the martian moon Phobos have been proposed [1-4].

Both carbonaceous (most oxidized) and enstatite (most reduced) chondrite clasts in Kaidun show signs of aqueous alterations that vary in type and degree and are most likely of pre-Kaidun origin [1, 4].

Objective: Our objective is to obtain a better understanding of the origin of the clasts in Kaidun, and of the processes that affected them prior to assembly in Kaidun. Our focus is on aqueously altered, enstatite (a-)chondrite clasts. These pre-alteration rocks are known to be highly reduced.

Here, we are using high-precision measurements of both ¹⁷O/¹⁶O and ¹⁸O/¹⁶O ratios in these clasts to examine the oxygen isotopic deviation, $\Delta^{17}\text{O}$, from the terrestrial mass fractionation line (TFL). $\Delta^{17}\text{O}$ may be a fingerprint for different parent bodies. The oxygen data are correlated with mineralogical observations.

Samples and Analyses: Nine completely clean clasts were separated and removed from Kaidun mount D6. Field emission gun scanning electron microprobe (FEGSEM), energy dispersive X-ray (EDX), electron backscatter diffraction (EBSD), and electron microprobe (EMPA) analyses of the lithologies and mineralogies were carried out at NASA Johnson Space Center and the University of Kyushu.

The $\Delta^{17}\text{O}$ values of the clasts were analyzed with the infrared laser heating-assisted fluorination system [5] at UCLA. Molecular O was extracted from 1-2 mg-sized samples (including duplicates), and the isotopic ratios measured on a gas source mass spectrometer (Delta Plus™). Analytical precision for $\Delta^{17}\text{O}$ is 0.02%.

Results: The clasts are comprised of the following lithologies: altered enstatite chondrites or aubrites, CM2, C1 (most likely CI1), C2, and a microbreccia.

Surviving E-chondrite or aubrite primary minerals include enstatite, augite, diopside, silica, plagioclase (albite to anorthite), ilmenite and heideite. Alteration products of the enstatite material are: poorly-crystalline enstatite, calcite, phyllosilicates, neoformed albite, and amphiboles (actinolite) (Fig. 1). Alteration mineralogy of the CM2 clast include Ca carbonates, tochilinite, serpentine, sulfides, and chromite. The intense alteration of CI1 clasts produces phyllosilicates, magnetite, sulfides, and Mg-Ca-Fe carbonates. C2 clasts contain phyllosilicates, magnetite, and sulfides. The microbreccia clast contains low-Ca pyroxene and Fe-rich olivine, which means it has no obvious relation to E-chondrites or aubrites.

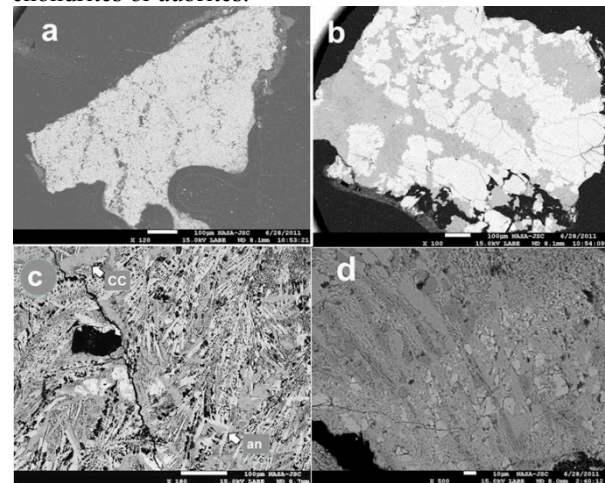


Figure 1. SEM (BSE) images of four altered enstatite chondrite or aubrite clasts from Kaidun: (a) relatively unaltered clast 5, containing poorly-crystalline enstatite and augite, (b) clast 6, containing enstatite, diopside, augite, ilmenite and albite, but also actinolite and secondary albite, (c) clast 7, consisting mainly of very poorly crystalline enstatite, box-form calcite (cc) and plagioclase crystals (an), with some residual silica, ilmenite and heideite, (d) partially altered clast 3a, containing enstatite, silica, plagioclase, calcite, and phyllosilicates.

The oxygen isotope results of the Kaidun clasts show a wide spread of $\delta^{18}\text{O}$ and $\Delta^{17}\text{O}$ values ($= \delta^{17}\text{O} - 0.528 * \delta^{18}\text{O}$) that covers the 3-oxygen-isotope fields occupied by several different meteorite groups, such as

the E-chondrites or aubrites, CM, and CI chondrites [6], and also 3-oxygen-isotope fields that are not (yet) correlated to a particular meteorite group.

Most clasts scatter around the TFL (terrestrial mass fractionation line) in their $\Delta^{17}\text{O}$, with both positive and negative values. The CM2 clasts lies on the AMF (Allende Mass Fractionation [7]) line ($\Delta^{17}\text{O} = -3$; Fig. 2).

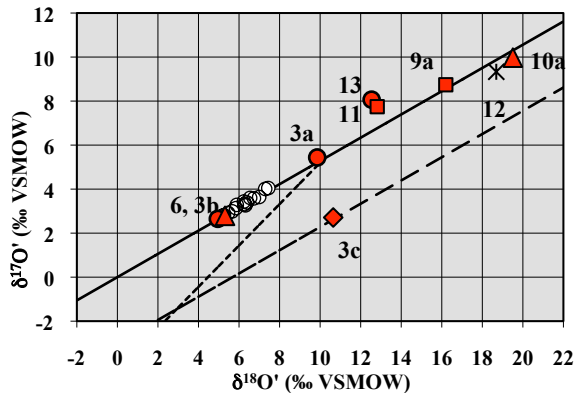


Figure 2. $\delta^{17}\text{O}'$ vs. $\delta^{18}\text{O}'$ plot of the Kaidun clasts. Solid line = TFL, short dashed line = CCAM (carbonaceous chondrite anhydrous mineral), long dashed line = AMF. Red symbols: circles = altered enstatite chondrites or aubrites, squares = C1 (possibly CI1), triangles = C2, diamond = CM2, asterisk = microbreccia. Numbers are sample numbers. White symbols: enstatite chondrite meteorites (UCLA data) for comparison.

Discussion: It was proposed [7] that the primitive oxygen isotopic composition of water ice might lie on the high- $\Delta^{17}\text{O}$ extension of the primitive slope-1.00 line [8]. Aqueous alteration of meteorites is indicated on a 3-oxygen-isotope plot in three consecutive stages: (1) shift towards more positive $\delta^{18}\text{O}'$ values, (2) shift towards more positive $\delta^{18}\text{O}$ and $\Delta^{17}\text{O}$ values, and (3) a further shift towards more positive $\delta^{18}\text{O}$ values [7].

The altered E-chondrites or aubrites in Kaidun (samples 6, 3a, 11) follow such an alteration sequence. Sample 6 still contains primary enstatite, diopside, and albite but also the alteration products actinolite (hydrated amphibole) and neoformed albite (Fig. 1b). Its oxygen isotopic values are representative of relatively unaltered E-chondrites (Fig. 2); however, the presence of amphibole may indicate a higher alteration temperature which can explain that the oxygen isotopic values have not shifted towards more positive values. Sample 3a contains calcite and phyllosilicates (Fig. 1c, d), thus it appears more altered than 6 in that it contains more water (phyllosilicates vs. amphiboles). Its oxygen isotopic values are more positive than that of 6 (Fig. 2). As expected from alteration by a high- $\Delta^{17}\text{O}$ water [8], its $\Delta^{17}\text{O}$ value has increased to +0.24‰ (from +0.03‰ of sample 6). Sample 11, which contains phyllosilicates, has an even higher $\Delta^{17}\text{O}$ value (+1.44‰), and

more positive $\delta^{18}\text{O}$ values. A line connecting samples 3a and 11 has a slope of 0.98, which is between those of the CCAM (0.94 [6]) and the slope-1 line (1.00 [8]) (Fig. 3). Both these lines indicate interactions of meteorites with an isotopically heavy water endmember.

Similarly, one could make the same argument for samples 9a, 12, and 10a as being altered CIs (Fig. 3), although their $\delta^{18}\text{O}$ values should be more positive for that scenario. Samples 13 (C1/CI1), 3b (C2), and 3c (CM2) are not related to these alteration sequences. However, sample 13 is highly altered, and accordingly shows a high $\Delta^{17}\text{O}$ value (+0.98‰).

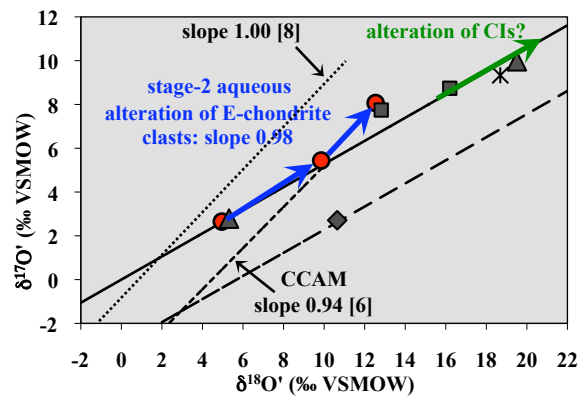


Figure 3. $\delta^{17}\text{O}'$ vs. $\delta^{18}\text{O}'$ plot of the Kaidun clasts highlighting the proposed alteration pathway (blue arrows) of the E-chondrite and aubrite fragments (in red). Samples 3a and 11 fall on a slope 0.98 line.

Conclusions: A variety of altered E-chondrite or aubrite lithologies in Kaidun were described earlier [1], and support the findings from this study. It is noted that (i) hydrated phases are abundant in all lithologies in Kaidun, whereas all other E-chondrites are entirely anhydrous, and (ii) the alteration products are highly variable in many minor element compositions. This indicates an incomplete and unequilibrated nature of the alteration process on the parent body and precludes that the alteration processes occurred on Kaidun itself [1]. Although aqueous alteration is unknown from E-chondrites or aubrites, these new data attest to the presence of water within E-chondrite parent bodies. We note that all of the largest E asteroids show spectroscopic evidence for the presence of water [9].

References: [1] Zolensky M. and Ivanov A. (2003) *Chemie der Erde*, 63, 185-246. [2] Ivanova, M.A. *et al.* (2005) *Solar System Research*, 39, 150-156. [3] Ivanov A. (2004) *Solar System Research*, 28, 97-107. [4] MacPherson G.J. *et al.* (2009) *Geochimica et Cosmochimica Acta*, 73, 5493-5511. [5] Sharp Z.D. (1990) *Geochimica et Cosmochimica Acta*, 54, 1353-1357. [6] Clayton R.N. and Mayeda T.K. (1999) *Geochimica et Cosmochimica Acta*, 63, 2089-2104 [7] Young E.D. *et al.* (1999) *Science*, 286, 1331-1334. [8] Young, E.D. and Russell, S.S. (1998) *Science*, 282, 452-455. [9] Rivkin A. *et al.* (1995) *Icarus*, 117, 90-100.