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The oxygen isotope composition of Almahata Sitta

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Abstract–Eleven fragments of the meteorite Almahata Sitta (AHS) have been analyzed for oxygen isotopes. The fragments were separately collected as individual stones from the meteorite's linear strewn field in the Nubian Desert. Each of the fragments represents a sample of a different and distinct portion of asteroid 2008 TC_3. Ten of the fragments span the same range of values of $\delta^{18}O$, $\delta^{17}O$, and $\Delta^{17}O$, and follow the same trend along the carbonaceous chondrite anhydrous minerals (CCAM) line as monomict and polymict members of the ureilite family of meteorites. The oxygen isotope composition of fragment #25 is consistent with its resemblance petrographically to an H5 ordinary chondrite. Our results demonstrate that a single small asteroidal parent body, asteroid 2008 TC_3, only 4 m in length, encompassed the entire range of variation in oxygen isotope compositions measured for monomict and polymict ureilites.

INTRODUCTION

The name "Almahata Sitta" (AHS) is applied collectively to some hundreds of stones that were found in a linear strewn field in the Nubian Desert coincident with the projected Earth-impacting orbit of asteroid 2008 TC_3 (Jenniskens et al. 2009; Shaddad et al. 2010). The meteorites were collected 2 to 5 months after the asteroid exploded in Earth's atmosphere on October 7, 2008. Sample collection was conducted by staff and students of the University of Khartoum, led by Prof. Muawia Shaddad (University of Khartoum) and Dr. Peter Jenniskens (SETI Institute).

Initial investigation focused on fragment #7 of the meteorite and identified it petrographically as a polymict ureilite, a carbonaceous ultramafic achondrite. Oxygen isotope compositions measured on aliquots of #7 were consistent with its identification as a ureilite but were not definitive because they did not exhibit the full range of heterogeneity typical of polymict ureilites (Jenniskens et al. 2009). The objective of the present study is to extend oxygen isotope analyses to a larger number of fragments of AHS to test whether or not it is legitimate to designate it as a polymict ureilite meteorite. We have analyzed 10 additional fragments of AHS. Our results demonstrate that AHS is a polymict member of the ureilite meteorite family.

Description of Analyzed Samples

The hundreds of individual stones of AHS recovered from the Nubian Desert are small in size, each weighing at most a few hundred grams, and heterogeneous. The stones differ in their infrared spectra, in their textures, in density, in porosity, in mineral chemistry and modal abundances, and in oxygen isotopic composition. The fragments present a jigsaw puzzle difficult to reassemble. The small size of the fragments in relation to an asteroidal body 4 m in length virtually guarantees that any reconstruction will never be fully commensurate with the original. Nevertheless, it is important to visualize asteroid 2008 TC_3 prior to impact in order to understand the nature of the observed heterogeneity. Was asteroid 2008 TC_3 a breccia produced in a single impact that disrupted the ureilite parent body? Did asteroid 2008 TC_3 consist of clasts repeatedly fragmented in a succession of impact-reaggregation–impact-reaggregation events, producing a breccia of breccias? Here an attempt is made to reconstruct asteroid 2008 TC_3 in order to understand the scale of its heterogeneity.

The explosive disruptions of asteroid 2008 TC_3 observed by European weather satellite Meteosat 8 at relatively high attitudes compared to other fireballs indicated that it was a weakly bound aggregation with a porosity as high as 50% (Borovička and Charvát 2009). Ground-based density measurements confirm a range of densities from as low as 1.48 for #7 to 3.08 g cm^{-3} for #4 measured by synchrotron X-ray computed microtomography (SXCT) with corresponding porosities, respectively, of 40 to 10% (Jenniskens et al. 2009; Zolensky et al. 2010). For the same samples, SXCT reveals a foliation of planar, mutually parallel pores in #7 compared to compact, mosaicized mineral grains in #4 (Zolensky et al. 2010). A foliation of planar pores defines surfaces of low strength along which the asteroid would easily break upon impact with the atmosphere. Measured infrared spectra of some 40 fragments show a range of variation in the relative abundances of olivine versus pyroxene from all olivine to all pyroxene (Sandford et al. 2010). Three distinct rock types have been identified from a study of 17 fragments including (1) pyroxene-dominated, very porous, and highly reduced, (2) pyroxene-dominated and compact, and (3) an olivine-dominated, compact lithology. The three lithologies include examples of typical ureilite smelting textures with pigeonite increasing in mg# and metal and silica phases appearing in proximity to graphite (Zolensky et al. 2010). The different rock types are distinct with no gradational transition from one to the other; some fragments show clasts of different lithologies within the same fragment (Zolensky et al. 2010). The compositions of olivine cores vary from 78 to 96 in mg#. Pyroxenes vary widely in composition from $En_{99}Wo_1$ to $En_{61}Wo_{37}$ (Zolensky et al. 2010).

The foregoing observations provide a basis for reconstructing asteroid 2008 TC_3 prior to its destruction. The asteroid consisted of clasts of both compact and porous lithologies, some dominated by olivine, some by pyroxene. Fragmentation occurred when the asteroid exploded in the stratosphere along porous, pre-existing surfaces of weakness showering hundreds of small stones in a linear trail across the Nubian Desert. Each fragment that has been collected and studied to date represents a distinct portion of the meteorite. It is true that all of the fragments are "paired" in the sense that they were all derived from the same parent body and all fell at the same time. But the parent body was, itself, a breccia, perhaps a breccia of breccia clasts. In some cases, the asteroid broke apart along weak surfaces that separated breccia clasts: in these cases, each fragment represents a single clast with a uniform catalog of properties. In other examples, explosive disruption cut across clast boundaries and the heterogeneity of the asteroid is readily visible in a single small stone. The oxygen isotope analyses should be understood in the light of the brecciated nature of the asteroid. Each fragment analyzed for oxygen isotopes has its own distinct mineralogy, texture, and porosity. Some of the "crumbs" obtained for oxygen isotope analysis after other investigators had finished their work may incorporate portions of different clasts. The analyses of the fragments give the range of compositions of a population of breccia clasts from a brecciated parent body. Because each fragment is quite small in relation to the size of the 4-meter-long asteroid, one can only be certain that the distance spanning a homogeneous clast was equal to the size of the observed fragment. Indeed, the reader is given fair warning: most of the investigations conducted to date and reported in this issue used different aliquots of each fragment. Even when the sample numbers are the same, it is not necessarily true that different types of measurements refer to the same material. Finally, owing to the very limited number and amount of samples that could be brought out of the Sudan, the various investigators did not necessarily work on fragments with the same sample numbers. There is an imperfect correlation between oxygen isotope analyses and petrographic, mineralogical, and textural observations reported herein.

Sample Preparation and Method of Analysis

Samples were received for oxygen isotope analysis from other consortium investigators in the form of small fragments ("crumbs") weighing 50 to 200 mg. All samples were examined under a 25× binocular microscope before preparation for analysis. The vial holding sample #25 contained submillimeter sand grains remaining from a density determination by previous investigators. The sand grains were removed by hand-picking before analysis. One grain of sample #7 rimmed by a fusion crust was not analyzed. Once visual examination had been completed and contaminants removed, each sample was gently crushed under ethanol in a boron nitride mortar and pestle to a grain size of approximately 0.5 mm. The crushed material was not sieved and consequently contained a range of grain sizes. The crushed sample was washed three times in

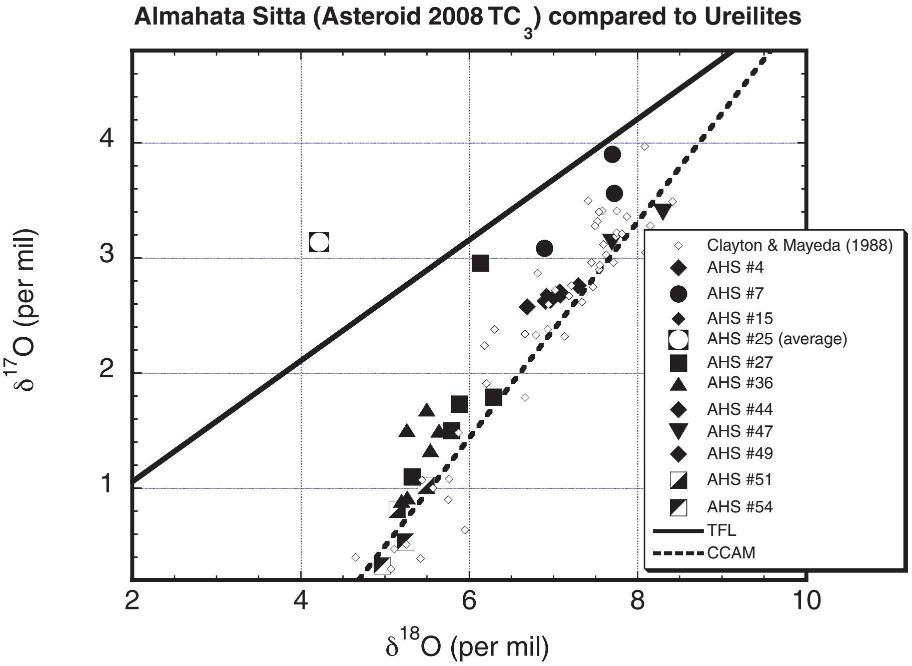

Fig. 1. Oxygen isotope composition of AHS. Analytical errors approximately equal to size of plotted data symbols. Analyzed fragments #4, #15, #44, and #49 are indistinguishable at the scale of the plot and are all shown with the same symbol, a filled diamond. The single symbol for #25 gives the average composition of three analyses. Data from Clayton and Mayeda (1988) are shown in smaller, unfilled diamonds.

deionized distilled water, ultrasonicated for 5 min in diluted HCl, and washed again three times in deionized distilled water. Material adhering to a hand magnet was removed from less magnetic components of the sample for separate analysis.

Samples weighing 2–3 mg were loaded for isotopic analysis in a reaction chamber designed by Sharp (1990). The reaction chamber with samples loaded was heated and evacuated for several hours, repeatedly fluorinated with 25 torr of BrF_5 and evacuated, and then fluorinated overnight. Evacuation and fluorination were repeated the next morning until measured room-temperature fluorination products noncondensable in liquid nitrogen were reduced to a negligible blank.

Analysis of individual samples was made by loading 25–30 torr of BrF_5 into the reaction chamber and heating the sample with an infrared laser (Synrad Inc., 30 watt, CO_2 laser, 10.6 micron wavelength). The spot size of the laser beam was defocused to a 100 mm diameter to minimize scattering of sample particles. The resulting mixture of O_2, SiF_4, and residual interhalogen compounds was purified by passage through two liquid nitrogen traps, and pumped by a single-stage mercury diffusion pump onto molecular sieve 5A chilled by liquid nitrogen. The purified sample was transferred to the dual inlet of a Thermo-Fisher MAT 252 mass spectrometer where the ion beams of $^{16}O^{16}O$, $^{16}O^{17}O$, and $^{16}O^{18}O$ were measured (Rumble and Hoering 1994). Every sample was tested for NF_3 and CF_4 contamination by scanning the mass range from 40 to 75 Da with a Faraday cup whose preamplifier resistor had a value of 3×10^{11} Ω.

Two aliquots of a reference material, Gore Mountain garnet (USNM 107144, obtained by courtesy of J. Post, Smithsonian Institution), were analyzed for every four unknowns. The reference garnet gives a value of $\delta^{18}O_{VSMOW}$ of 6.0 per mil in comparison to UWG-2 (Valley et al. 1995; Rumble et al. 1997). The two sigma standard deviations of Gore Mountain garnet analyses measured during the course of this study were as follows: $\Delta^{17}O \pm 0.03$, $\delta^{17}O \pm 0.09$, and $\delta^{18}O \pm 0.17$ per mil. The value used for the slope of the terrestrial fractionation line (TFL) in this study is 0.526 ($\pm$0.001) (Rumble et al. 2007).

RESULTS

Aliquots of the first sample of AHS analyzed, #7, lay at the upper end of the ureilite field when plotted on a $\delta^{18}O$ versus $\delta^{17}O$ diagram (Clayton and Mayeda 1988, 1996; Jenniskens et al. 2009). Analyses of an additional 10 fragments of the meteorite show that its oxygen isotope compositions follow the ureilite trend extending from near the TFL parallel to the carbonaceous chondrite anhydrous minerals (CCAM) line to values of $\Delta^{17}O$ of −2.2‰ (Fig. 1, Table 1). The

Table 1. Oxygen isotope compositions of Almahata Sitta (AHS).

Sample	Run	$\Delta^{17}O$	$\delta^{17}O$	$\delta^{18}O$
AHS #4	16-101	−1.032	2.63	6.99
	16-102	−1.005	2.62	6.90
AHS #7	15-310	−0.147	3.90	7.70
	15-311	−0.501	3.56	7.72
	15-312	−0.539	3.09	6.89
AHS #15	16-222	−0.955	2.68	6.92
	16-228	−0.948	2.57	6.68
AHS #25	16-223	0.676	2.96	4.34
	16-229	0.964	3.25	4.35
	16-234	1.127	3.21	3.96
AHS #27	16-225	−1.366	1.73	5.89
	16-230	−0.269	2.96	6.13
	16-240	−1.516	1.79	6.29
	16-241	−1.700	1.10	5.32
	16-243 (magnetic)	−1.546	1.50	5.79
AHS #36	16-224	−1.842	0.89	5.20
	16-232	−1.204	1.69	5.50
	16-235	−1.849	0.92	5.26
	16-236 (magnetic)	−1.581	1.33	5.53
	16-239	−1.259	1.51	5.26
	16-244 (magnetic)	−1.466	1.50	5.64
AHS #44	16-210	−1.015	2.71	7.07
	16-216	−1.074	2.76	7.29
AHS #47	16-99	−0.968	3.40	8.30
	16-100	−0.911	3.14	7.69
AHS #49	16-211	−0.940	2.58	6.69
	16-218	−1.044	2.68	7.08
AHS #51	16-212	−1.858	1.03	5.49
	16-213 (magnetic)	−1.889	0.82	5.15
AHS #54	16-217	−2.288	0.32	4.96
	16-219	−2.225	0.53	5.24

TFL is a linear trend defined by whole rock analyses of igneous, sedimentary, and metamorphic terrestrial rocks (Clayton and Mayeda 1983; Rumble et al. 2007). The CCAM line is the locus of analytical points for the minerals separated from refractory inclusions of the Allende meteorite (Clayton and Mayeda 1999). Such a range of oxygen isotope compositions in a ureilite polymict breccia is not unexpected. Analyses of clasts and whole rock matrix from the Nilpena brecciated ureilite show a range in $\delta^{18}O$ from 5.4 to 8.1‰ and a range in $\Delta^{17}O$ from −0.6 to −1.4‰ (Clayton and Mayeda 1988, 1996). Spot analyses of mineral grains in the polymict ureilite Dar al Gani with an ion microprobe range from 4.0 to 9.0‰ in $\delta^{18}O$ and from +0.0 to −2.5‰ in $\Delta^{17}O$ (Kita et al. 2004). Heterogeneity in oxygen isotopic compositions of similar magnitude was measured in the polymict ureilites Elephant Moraine (EET) 83309 and EET 87720 using an ion microprobe (Downes et al. 2008).

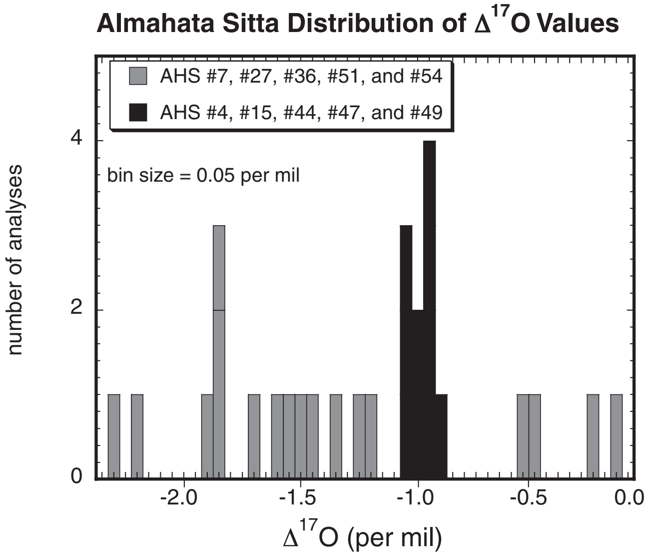

Fig. 2. Histogram of AHS $\Delta^{17}O$ values. Bin size = 0.05 per mil. Fragments #4, #15, #44, #47, and #49 form a subgroup at $\Delta^{17}O = -1.0$ (±0.1). The compositions of other fragments extend over the entire range in $\Delta^{17}O$ values known for ureilites.

There is a distinct clumping of oxygen isotope compositions for samples #4, #15, #44, and #49 so that their plotted data points are mutually obscuring (Fig. 1). The compositions of samples #4, #15, #44, and #49 are shown separately in the histogram of Fig. 2. These four samples, together with #47, show a limited variation in $\Delta^{17}O$, from −1.07 to −0.91‰ (Table 1). Franchi (2008) observed subgroups of ureilite analyses at discrete $\Delta^{17}O$ values, in particular at −0.98‰ (0.075‰ bin). Almahata Sitta analytical results for #4, #15, #44, #47, and #49 lie within Franchi's subgroup. This subgroup may delineate the most abundant clasts in AHS, but with only 11 fragments analyzed of some 300 recovered stones, a representative sampling has probably not been acquired as yet.

The correlation between the mg# of olivine core compositions and both $\delta^{18}O$ or $\Delta^{17}O$ is a benchmark for studies of ureilites (Clayton and Mayeda 1988). Secondary ion microprobe and electron microprobe studies have demonstrated the correlation with closely spaced spot analyses of olivine Fe/Mg and oxygen isotope compositions (Kita et al. 2004; Downes et al. 2008). The current results (Fig. 3) only hint at the correlation owing to a lack of colocated analyses of both Mg/(Mg + Fe) and $\Delta^{17}O$. In a recent written communication, C. Goodrich reported finding an olivine core with an mg# of 95 in a fragment of AHS #54 in contrast to the value of 79 shown in Fig. 3. If an mg# value of 95 were used in plotting AHS #54 on Fig. 3, a much improved correlation with the Clayton and Mayeda (1988) trend would be seen.

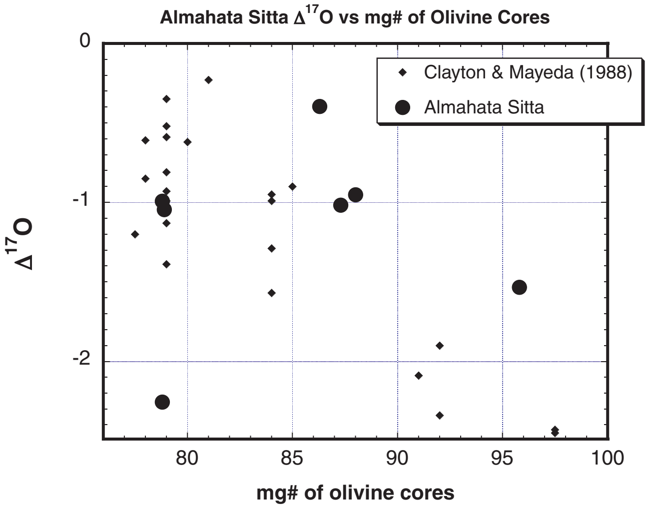

Fig. 3. Variation of olivine core mg# with $\Delta^{17}O$. Almahata Sitta fragments #4, #7, #15, #36, #44, #49, and #54 are plotted with average values of $\Delta^{17}O$ and mg#. Olivine core compositions from Zolensky et al. (2010). The comparison of in situ spot analyses for Mg/(Fe + Mg) in olivine with bulk analyses of oxygen isotopes may lead to imperfect correlations because analyses are not colocated (see text). Note that $\Delta^{17}O$ values measured for #36 (average plotted at $\Delta^{17}O = -1.5$) range from −1.2 to −1.8 per mil.

Magnetic and less magnetic fractions of AHS were separated for analysis where sufficient sample was available. Analysis of both magnetic and less magnetic fractions of #27, #36, and #51 (see Table 1) show differences in composition that are smaller than the heterogeneity of the entire sample population.

DISCUSSION

Exotic clasts have been identified in a number of ureilite meteorites (Ikeda et al. 2000, 2003). Oxygen isotope analyses indicate a number of possible exotic clasts in AHS. Sample #25 has been identified petrographically as an "H5" ordinary chondrite, a result that is consistent with its oxygen isotope composition (Zolensky et al. 2010). It may be an exotic clast included within the polymict ureilite breccia or it may be an adventitious prior fall accidentally picked up during sample collection.

Samples AHS #7, #27, and #36 show a range of oxygen isotope values (Table 1) that may result from the incorporation of exotic clast material in the analyzed bulk material. A similar range in composition is seen in the in situ spot analyses of exotic clasts in ureilites made by Kita et al. (2004) and Downes et al. (2008). Exotic clasts are interpreted to represent samples of impactors that bombarded the ureilite parent body (Downes et al. 2008).

The subgroup of fragments #4, #15, #44, #47, and #49 that share a limited range in $\Delta^{17}O$ values, may record a localized volume of limited size within the ureilite parent body where mineral–mineral oxygen isotopic exchange and equilibration took place (Ash et al. 2000; Franchi 2008).

The remarkable heterogeneity in oxygen isotope compositions measured previously in monomict ureilites and the observation of the same large range in variation in clasts from polymictic ureilites suggests that all of the family members may have originated on the same planetary body (Clayton and Mayeda 1988, 1999; Kita et al. 2004; Downes et al. 2008). Almahata Sitta was broken into hundreds of pieces during its explosive atmospheric passage, but it is clear that the 4 m asteroid 2008 TC_3 was a body displaying the same extreme heterogeneity seen in hand-specimens of polymict ureilites. Thus, direct evidence of the oxygen isotope heterogeneity of a single asteroidal ureilite parent body is now literally in-the-hand.

A similarity between AHS ureilites and Dar al Gani (Libya) ureilites has been noted by H. Downes (written communication). The several dozen stones, both monomict and polymict of Dar al Gani, show a heterogeneity that spans the entire published range in oxygen isotope compositions of ureilites just as do the fragments of AHS.

CONCLUSIONS

The many fragments that compose the AHS samples all were once part of a single asteroidal body, asteroid 2008 TC_3. The measured oxygen isotope compositional range of the meteorite spans the field of both monomict and polymict ureilites. The fragments display the same range of values of $\delta^{18}O$, $\delta^{17}O$, and $\Delta^{17}O$ and the same pattern of variation as other members of the group. Available data suggests a subgroup of fragments (#4, #15, #44, #47, and #49) may have achieved intermineral oxygen isotopic exchange with mass-dependent fractionation within a limited volume of the ureilite parent body.

Almahata Sitta is likely to have originated on a heterogeneous parent body, together with other members of the ureilite clan, that melted and recrystallized rapidly before oxygen isotope exchange and equilibration could be achieved throughout the body.

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