Tuesday, March 2, 2010
UREILITIC ASTEROIDS: INSIGHTS FROM ALMAHATA SITTA
1:30 p.m. Waterway Ballroom 1

Chairs: **Jason Herrin**
Scott Sandford

1:30 p.m. Herrin J. S. * Ito M. Zolensky M. E. Mittlefehldt D. W. Jenniskens P. M. Shaddad M. H.
Thermal History and Fragmentation of Ureilitic Asteroids; Insights from the Almahata Sitta Fall **[#1095]**
We detail the thermal history of recovered fragments of asteroid 2008 TC3 (the Almahata Sitta ureilite) and compare the size of fragments within TC3 to those initially dislodged from the ureilite parent body.

1:45 p.m. Welten K. C. * Meier M. M. M. Caffee M. W. Nishiizumi K. Wieler R. Jenniskens P. Shaddad M. H.
High Porosity and Cosmic-Ray Exposure Age of Asteroid 2008 TC3 Derived from Cosmogenic Nuclides **[#2256]**
Cosmogenic radionuclides in the Almahata Sitta ureilite, combined with measured size of 28 m^3, indicate that asteroid 2008 TC3 had a density of 1.5 g/cm^3 and a porosity of 55%. Cosmogenic noble gas concentrations indicate a cosmic-ray exposure age of 15 Myr.

2:00 p.m. Mikouchi T. * Zolensky M. Takeda H. Hagiya K. Ohsumi K. Satake W. Kurihara T. Jenniskens P. Shaddad M. H.
Mineralogy of Pyroxene and Olivine in the Almahata Sitta Ureilite **[#2344]**
Two Almahata Sitta samples (7 and 3-1) analyzed are two unique members of ureilites with possible genetical relationship on the same parent body. All low-Ca pyroxenes have a pigeonite crystal structure, suggesting the formation at high temperature.

2:15 p.m. Rumble D. * Zolensky M. E. Friedrich J. M. Jenniskens P. Shaddad M. H.
Oxygen Isotope Composition of Almahata Sitta **[#1245]**
It is demonstrated that a single asteroidal body, asteroid 2008 TC3, contained clasts representative of all known ureilite monomict and polymict ureilites in their oxygen isotope compositions.

2:30 p.m. Qin L. * Rumble D. Alexander C. M. O'D. Carlson R. W. Jenniskens P. Shaddad M. H.
Chromium Isotopic Composition of Almahata Sitta **[#1910]**
The $\varepsilon^{54}Cr$ values of Almahata Sitta samples are similar to that of HEDs. This suggests that they are derived from a parent body that is different from that of known carbonaceous chondrites. No correlation was found between $\varepsilon^{54}Cr$ and $\Delta^{17}O$.

2:45 p.m. Sandford S. A. * Milam S. N. Nuevo M. Jenniskens P. Shaddad M. H.
Infrared Spectroscopy of Samples from Multiple Stones from the Almahata Sitta Meteorite **[#1229]**
The infrared spectra of samples from 26 different stones from the Almahata Sitta meteorite strewn field will be presented.

THERMAL HISTORY AND FRAGMENTATION OF UREILITIC ASTEROIDS; INSIGHTS FROM THE ALMAHATA SITTA FALL. J.S. Herrin[1], M. Ito[1,2], M.E. Zolensky[1], D.M. Mittlefehldt[1], P.M. Jenniskens[3] and M.H. Shaddad[4], [1]NASA Johnson Space Center, Houston, USA. e-mail: jason.s.herrin@nasa.gov. [2]Lunar & Planetary Institute, Houston, USA, [3]SETI Institute, Mountain View, USA; [4]Physics Dept., University of Khartoum, Sudan.

Introduction: Asteroid 2008 TC3 was discovered on an Earth-intersecting trajectory just prior to entry into Earth's atmosphere. Recovery of ureilite meteorite fragments from the fall provides a unique opportunity to compared remotely sensed spectral data with laboratory determined mineralogy and composition. The event has also provided insight into the nature of ureilitic objects in space. In particular, the inferred low density (2200 kg/m^3) of the object combined with near-complete disintegration upon entry suggest a porous and loosely-consolidated body [1]. Accordingly, recovered fragments are small in size (1.5-283g) and represent several different ureilite lithologies. Some recovered fragments appear brecciated while others do not. We use chemical and mineralogic data to dissect the thermal history of this new ureilite, and then use this information to compare the inferred size of fragments within the asteroid to those initially dislodged from a common ureilite parent body (UPB).

Samples and Methods: Polished specimens were prepared from several recovered fragments of Almahata Sitta. Approximately half of these have typical (monomict) ureilite texture, consisting mostly coarse (100-2000µm) olivine and pyroxene with minor graphite and interstitial metal. Other fragments, such as those described in [1], are ureilitic breccias made up of mm-scale clasts or enclaves of fine-grained, porous olivine-dominated and pyroxene-dominated sublithologies whose boundaries are sometimes poorly defined but often separated by carbon-phase+metal+sulfide and/or voids. We performed electron probe microanalyses of silicate minerals at NASA Johnson Space Center. Preliminary measurements of trace elements, including REE, were also performed at NASA Johnson Space Center using a New Wave SS193nm laser ablation system coupled to a Thermo Element 2/XR mass spectrometer (LA-ICP-MS).

Thermal history of Almahata Sitta; the story of ureilites

Stage 1: Heating and partial melting. Ureilites are asteroid mantle rocks wherein temperatures of basaltic magmatism were sustained for timespans sufficient for extraction of magma. Preliminary results from LA-ICP-MS analyses reveal that the trace element compositions of Almahata Sitta silicate minerals are highly fractionated from chondritic relative abundances, being highly depleted in elements that are highly incompatible in residual solids during partial melting. This chemical fractionation is typical of ureilites and has been interpreted to have resulted from 25-30% loss of silicate partial melts [2].

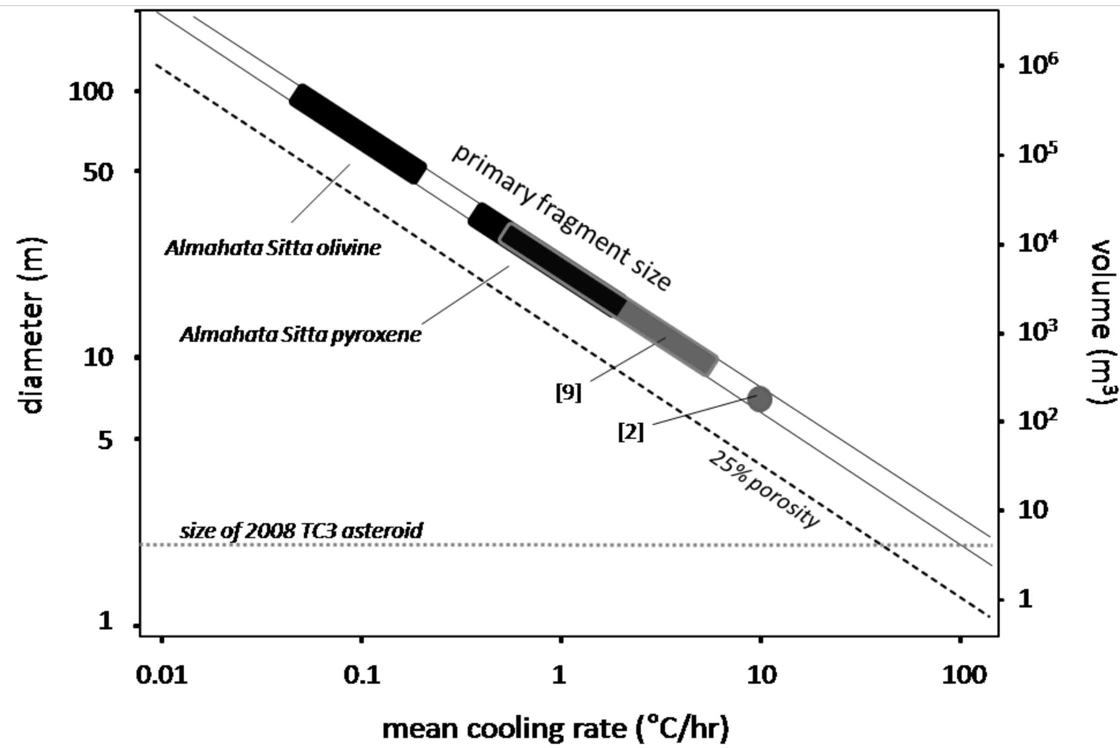
Stage 2: Disruption of hot UPB mantle. A favored topic in ureilite petrology is the catastrophic disruption of the UPB, a large (>200 km diameter [3]) asteroid that existed in for a brief period in the early solar system [4]. Converging lines of evidence reveal that the UPB mantle underwent massive fragmentation while still hot [3]. In Almahata Sitta, two-pyroxene equilibrium temperatures [5] derived from augite-bearing fragments reveal that final mantle equilibrium was 1190±65°C, at or near temperatures of partial melting. Temperatures from other augite bearing ureilites (ALH 84136, EET 96293, LEW 88201, META78008) span the range 1185-1255°C.

The high-mg# rims observed on Almahata Sitta olivines are a characteristic feature of ureilites. They are thought to record a short-duration reduction event resulting from sudden loss of pressure favoring the reaction $FeO + C \rightarrow Fe + CO$, which requires massive expansion in volume to proceed. In a fine-grained pyroxene-dominated sublithology of Almahata Sitta we observe that in contact with an interstitial silica phase low-Ca pyroxene also exhibits high-mg# rims 4-6 µm in thickness containing Fe-metal inclusions, suggesting the preserved reduction mechanism $MgFeSi_2O_6 + C \rightarrow MgSiO_3 + Fe + SiO_2 + CO$. The temperature of this reaction is constrained by the pigeonite smelting thermometer of [6], yielding reaction temperature estimates of 1295±25°C, within the 1150-1300°C range of most ureilites.

Stage 3: Rapid cooling. Upon disruption of the UPB mantle, dislodged fragments began to cool rapidly. Below smelting temperatures, cooling rates were rapid enough to preserve mg# zoning at grain margins. We use this observed disequilibrium in olivine and pyroxene from Almahata Sitta to estimate minimum cooling rates using the asymptotic cooling model of [7] and Fe-Mg interdiffusion kinetics of olivine [8] and pyroxene [7]. From initial temperatures of 1200-1300°C down to 800°C, mean cooling rates of 0.4-2°C/h and 0.05-0.2°C/h were estimated from pyroxene and olivine, respectively. Such rapid cooling rates are consistent with previous estimates based high-mg# olivine rims in other ureilites [9,2].

Stage 4: Cold re-accretion. Sometime after the aforementioned catastrophe, fragments of the UPB mantle re-accreted into smaller daughter asteroids with insufficient latent or radiogenic heat to exceed silicate mineral mineral blocking temperatures. If these second-

generation ureilitic asteroids still exist in the asteroid belt today, then they are perhaps parental to objects like 2008 TC3 that deliver ureilites to Earth.



Estimated mean cooling rates of ureilites compared with sizes of spherical bodies with equivalent mean cooling rates. Sizes of dislodged "primary fragments" of UPB mantle implied by Almahata Sitta minerals are much larger than asteroid 2008 TC3 or fragments within, suggesting significant subsequent fragmentation has occurred at cool temperatures.

Fragmentation of 2008 TC3 and break-up of UPB mantle

Despite observed textural and mineralogic variation between and within specimens, all recovered lithologies of Almahata Sitta contain only ureilitic material, with the possible exception of an H5 chondrite (Sample 25) recovered from the strewn field that may or may not be part of the Almahata Sitta fall. Fragments of Almahata Sitta lack features of true "regolithic polymict ureilites" (such as EET 83309 and EET 87720) that are finely brecciated and contain rounded clasts, Fe,Si-metals, and xenogenic materials. It is possible that the fragmented and porous nature of 2008 TC3 is typical of modern ureilitic asteroids and not limited to their regoliths. To compare fragmentation resulting from catastrophic disruption of the UPB with fragment size within 2008 TC3, we estimated the initial size of hot dislodged fragments of UPB mantle from estimated cooling rates using the heat diffusion equation of [10], ignoring negligible effects of surface radiation and internal heat production. We applied range of relevant thermal diffusivity from 5e-7 [11] to 6.3e-7 m^2/s [12] and also considered the effect of high porosity, which might decrease thermal diffusivity to as low as 2e-7 m^2/s [13]. Mean cooling rates inferred from ureilite mineral rims would be experienced by spherical bodies 10-100 m in diameter. By contrast, asteroid 2008 TC3 was approx-imately 2 m in diameter and composed of many smaller fragments, likely on the order of centimeters to tens-of-centimeters and thus much smaller than typical fragments initially dislodged from hot UPB mantle. We infer that after breakup of the UPB subsequent fragmentation, either prior to or after accretion of daughter asteroids, must have occurred by a process that did not result in mixing with significant quantities of non-ureilitic components. However, since diffusion profiles alone can provide only minimum cooling rates, the true minimum size of hot primary UPB mantle fragments cannot be known with absolute certainty by these me-thods. Future work might incorporate mass balance of phases and diffusion of minor elements in order to better constrain initial zoning profiles and cooling rates.

References: [1] Jenniskens et al., 2009. Nature 458:485-488. [2] Goodrich et al., 2004. Chemie de Erde 64:283-327. [3] Walker & Grove, 1993. Meteoritics 28:629-636. [4] Warren & Huber, 2006. MAPS 41:835-849. [5] Brey & Kohler, 1990. J. of Petrology 31:1353–1378. [6] Singletary & Grove, 2003. MAPS 38:95-108. [7] Ganguly et al., 1994. GCA 58:2711-2723. [8] Chakraborty, 1994. Phys Chem Minerals 21:489-500. [9] Chikami et al., 1996. 27th LPSC Abs#1111. [10] Carslaw & Jaeger, Conduction of Heat in Solids, 2nd ed., 510 pp., Claren-don, Oxford, 1959, p234. [11] Gupta & Sahidjpal, 2009. 40th LPSC Abs#1530. [12] Clauser & Huenges, Thermal conductivity of rocks and minerals, in: T.J. Ahrens (Ed.), Rock Physics and Phase Relations: A Handbook of Physical Constants, AGU, Washington, DC, 1995, pp105–126. [13] Yomogida & Matsui, 1983. JGR 88:9513-9533.

HIGH POROSITY AND COSMIC-RAY EXPOSURE AGE OF ASTEROID 2008 TC3 DERIVED FROM COSMOGENIC NUCLIDES.
K. C. Welten[1], M. M. M. Meier[2], M. W. Caffee[3], K. Nishiizumi[1], R. Wieler[2], P. Jenniskens[4], M. H. Shaddad[5] , [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA (E-mail: kcwelten@berkeley.edu), [2]Department of Earth Sciences, ETH Zürich, CH-8092 Zürich, Switzerland, [3]Department of Physics, Purdue University, West Lafayette, IN 47907, USA. [4]SETI Institute, Carl Sagan Center, 515 North Whisman Road, Mountain View, CA 94043, USA. [5]Department of Physics, University of Khartoum, P.O. Box 321, Khartoum 11115, Sudan.

Introduction: On October 7, 2008, a small asteroid, 2008 TC3, exploded in the atmosphere at an altitude of 37 km above the Nubian Desert of northern Sudan. Several search expeditions yielded 300 meteorite fragments with a total mass of ~4 kg. The meteorite, known as Almahata Sitta, was classified as an anomalous polymict ureilite [1].

The pre-atmospheric size of Almahata Sitta was determined directly from observations of asteroid 2008 TC3 before impact, yielding a volume of 28±6 m^3 [2], corresponding to a radius of 1.88±0.12 m. However, the bulk density of the object is unknown, while the density of the recovered meteorites ranges widely, from 1.77 to 3.26 g/cm^3. In this work, we report the cosmogenic radionuclide noble gas concentrations, to constrain the pre-atmospheric mass (and density) of asteroid 2008 TC3 and determine its cosmic-ray exposure (CRE) age.

Experimental Methods: We received small chips of six Almahata Sitta fragments (#1, 4, 15, 36, 44, 47) for radionuclide measurements and four (#4, 36, 44, 47) for noble gas analysis. We dissolved 50-100 mg, along with 3-5 mg of Be and Cl, in concentrated HF/HNO_3. After dissolution, a small aliquot was taken for chemical analysis by atomic absorption spectrometry. We separated Be, Al and Cl using ion exchange and acetyl-acetone extraction techniques. AMS measurements of ^{10}Be and ^{36}Cl were performed at PRIME lab [3]. The concentrations and isotopic composition of light noble gases were measured in chips of 30-150 mg, following procedures described previously [4]. Results of the chemical, radionuclide and noble gas analysis are summarized in Table 1.

Radionculide results. The ^{10}Be concentrations of 19-24 dpm/kg are surprisingly high for a 4-meter object. The cosmogenic ^{36}Cl concentrations range from 3.6 to 15.3 dpm/kg, mainly due to variations in Fe (7.6-20.8 wt%) and Ca (0.9-5.8 wt%), the main targets elements for ^{36}Cl production (Fig. 1). When normalized to Fe and Ca, using $P(^{36}Cl)_{Ca} = 10*P(^{36}Cl)_{Fe}$, the results yield a relatively constant ^{36}Cl concentration of 20 ± 1 dpm/kg[Fe+10Ca]. To match the measured radionuclide concentrations with calculated depth profiles for a fixed radius of 1.88 m, we varied the density of the object from 1.0 to 2.3 g/cm^3 (which corresponds to chondritic objects with radii of 50 to 120 cm, i.e. 180-430 g/cm^2), using the chemical composition of individual samples (Table 1) and elemental production rates for chondrites with radii of 180-430 g/cm^2 [5].

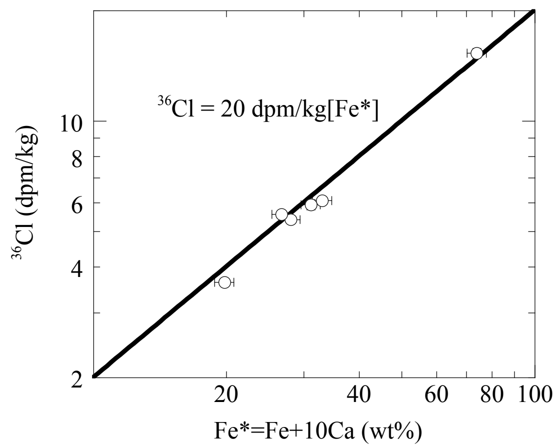


Figure 1. Correlation of ^{36}Cl concentrations in Almahata Sitta samples vs. chemical composition. The solid line represent a linear fit with a slope of 20 dpm/kg[Fe+10Ca].

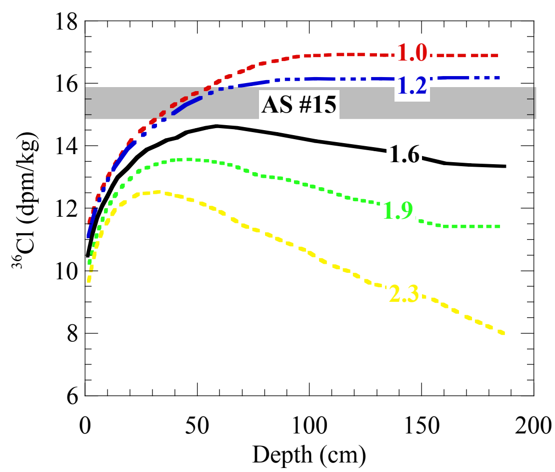


Figure 2. Comparison of measured ^{36}Cl concentrations in AS #15 (grey bars) with calculated depth profiles in objects with R=188 cm and density =1.0-2.3 g/cm^3.

Figure 2 shows that the high ^{36}Cl concentration in Almahata fragment #15 is only consistent with average meteoroid densities of 1.2-1.6 g/cm^3. The ^{36}Cl concentrations in other Almahata fragments yield similar densities, with a value of ~1.5 g/cm^3 yielding the best fit with both ^{10}Be and ^{36}Cl concentrations. Assuming an average grain density of ~3.3 g/cm^3 for ureilites, the low bulk density thus implies that asteroid 2008 TC3 had a total porosity of ~50%. The bulk density of this small asteroid is lower than the measured densities of 1.77-3.26 g/cm^3 of the recovered meteorite fragments (Fig. 3). This high porosity of asteroid 2008 TC_3 is similar to - but more accurate than - the estimated porosity based on the atmospheric fragmentation of the asteroid as observed by Meteosat 8 [8].

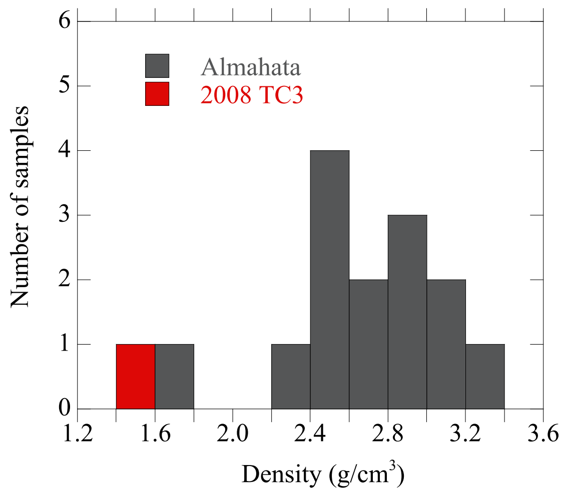


Figure 3. Bulk density of asteroid 2008 TC_3 (red) in comparison with measured densities of individual meteorite fragments (grey) from the Almahata Sitta strewnfield.

Noble gases and CRE age. Concentrations of cosmogenic ^{3}He and ^{21}Ne are relatively constant at 22-28 and 5.8-7.8, respectively. The shielding-sensitive $(^{22}Ne/^{21}Ne)_{cos}$ ratio is also quite constant (around 1.05-1.06) in all samples except sample #44. This sample has a higher value of ~1.10, indicating that it had been closer to the pre-atmospheric surface than the others. We calculated production rates as a function of ^{22}Ne/^{21}Ne, after taking into account that the ^{22}Ne/^{21}Ne ratios in ureilites are systematically ~2% lower than in L-chondrites [7,8]. We used chemical correction factors for each individual sample, since the major element concentrations in the Almahata Sitta ureilite vary significantly from sample to sample (Table 1). Calculated ^{3}He and ^{21}Ne production rates (in units of 10^{-8} cm^3 STP/g/Myr) range from 1.68-1.72 (^{3}He) and 0.38-0.54 (^{21}Ne). These values yield average ^{3}He and ^{21}Ne ages of 14.9±1.8 Myr and 14.5±0.9 Myr, respectively. Similar ages of 12-14 Myr are reported for two fragments measured by Ott [9]. The average age of ~15 Myr is in the range of typical ureilite ages of 1-50 Myr [8].

Conclusions. The relatively high concentrations of cosmogenic ^{10}Be and ^{36}Cl in six fragments of the Almahata Sitta ureilite strewnfield indicate that they came from an object with a radius of 260-300 g/cm^2. Given the pre-atmospheric radius of Almahata Sitta of ~1.9 m as determined from direct observations of asteroid 2008 TC3 before its impact on Earth, this constrains its bulk density to 1.5 ± 0.1 g/cm^3 and its porosity to 55 ± 5 %.

With the reflectance spectrum of 2008 TC3 being consistent with F-class asteroids, the discovery of the surviving meteorite fragments of Almahata Sitta firmly links polymict ureilites to F-class objects, which are mainly found at a semi-major axis of ~2.45 AU, near the 3:1 mean motion resonance with Jupiter. The cosmogenic ^{3}He and ^{21}Ne concentrations in four Almahata Sitta fragments yield a consistent CRE age of ~15 Myr. This age represents the transfer time of asteroid 2008 TC3 from an F-type parent body in the asteroid belt to Earth [10].

Acknowledgments. This work was supported by NASA grant NNG06GF22G, the Planetary Astronomy program and the Swiss National Science Foundation.

References: [1] Jenniskens P. et al. (2009) *Nature* 458, 485. [2] Scheirich P. et al. (2009) DPS 41. [3] Sharma P. et al. (2000). *NIM* B172, 112. [4] Wieler R. et al. (1989) *GCA* 53, 1449. [5] Leya I. and Masarik J. (2009) *MAPS* 44, 1061. [6] Borovicka J. and Charvat Z. (2009) *A. & A.* 507, 1015. [7] Aylmer D. et al. (1990) *GCA* 54, 1775. [8] Rai V. K. et al. (2003) *GCA* 67, 4435 [9] Ott U. et al. (2010) *LPSC* 41, #1195. [10] Jenniskens P. et al., submitted to *MAPS*.

Table 1. Concentrations of major elements (in wt%) and cosmogenic ^{10}Be and ^{36}Cl (in dpm/kg) and ^{3}He, ^{21}Ne (in 10^{-8} cm^3 STP/g) and cosmogenic ^{22}Ne/^{21}Ne ratio in Almahata Sitta ureilite samples.

Sample	Mg	Al	Ca	Mn	Fe	Ni	^{10}Be	^{36}Cl	^{36}Cl*	^3He_c	$^{21}Ne_c$	$(^{22}Ne/^{21}Ne)_c$
#1	19.6	0.16	0.92	0.28	20.8	0.37	19.0±0.4	5.9±0.2	19.7±0.6	–	–	–
#4	20.9	0.29	1.72	0.38	9.7	0.05	22.5±0.9	5.4±0.1	20.0±0.4	22.0	7.01	1.058
#15	17.0	0.43	5.75	0.32	15.2	0.14	19.6±0.4	15.3±0.5	21.1±0.6	–	–	–
#36	23.7	0.17	1.12	0.31	7.6	0.03	21.9±0.4	3.6±0.1	19.4±0.5	24.2	7.25	1.062
#44	19.5	0.28	1.73	0.30	14.6	0.16	21.4±0.4	6.1±0.1	19.1±0.4	27.0	5.78	1.098
#47	20.1	0.14	1.05	0.28	15.1	0.17	24.1±0.9	5.6±0.1	21.8±0.5	27.8	7.83	1.045

*normalized to Fe+10Ca

MINERALOGY OF PYROXENE AND OLIVINE IN THE ALMAHATA SITTA UREILITE. T. Mikouchi[1], M. Zolensky[2], H. Takeda[1], K. Hagiya[3], K. Ohsumi[4], W. Satake[1], T. Kurihara[1], P. Jenniskens[6] and M. H. Shaddad[7], [1]Dept. of Earth and Planet. Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan (mikouchi@eps.s.u-tokyo.ac.jp), [2]NASA Johnson Space Center, Houston, TX 77058, USA, [3]Graduate School of Life Sci., University of Hyogo, Kamigori-cho, Hyogo 678-1297, Japan, [4]JASRI, Sayo-cho, Hyogo 679-5198, Japan, [5]SETI Institute, Mountain View, CA 94043, USA, [6]Physics Dept., University of Khartoum, Khartoum 11115, Sudan.

Introduction: The Almahata Sitta meteorite (hereafter “Alma”) is the first example of a recovered asteroidal sample that fell to earth after detection still in the orbit (2008TC$_3$ asteroid), and thus is critical to understand the relationship between meteorites and their asteroidal parent bodies [1]. Alma is a polymict ureilite showing a fine-grained brecciated texture with variable lithologies from black, porous to denser, white stones [1]. It is an anomalous ureilite because of wide compositional ranges of silicates with abundant pores often coated by vapor-deposit crystals [1]. Nevertheless, Alma has general similarities to all ureilites because of reduction textures of silicates suggestive of rapid cooling from high temperature as well as heterogeneous oxygen isotope compositions [e.g., 1-5]. Alma is especially unique because it spans the compositional range of known ureilites [1]. In this abstract we report detailed mineralogical and crystallographic investigations of two different fragments to further constrain its thermal history with regards to the nature of the ureilite parent body.

Petrography: The analyzed fragments (#7 and #3-1) show distinct color. The #7 sample (“Alma7”) is the one originally described in [1], which is dark colored. In contrast, #3-1 (“Alma3-1”) is rather white partly covered with black fusion crust. In spite of the color difference, both fragments have a similar sponge-like (because of pores) fine-grained polycrystalline texture, being mainly composed of olivine and pyroxene with Fe(-Ni) metal and carbon phases. The texture is generally similar to that of mosaicized ureilites such as Haverö, Y-74154 and ALH81101 (Fig. 1) [e.g., 6]. We note that the pyroxene-rich area in Alma7 shows a similar mosaicized or mottled texture to olivine, but each minute pyroxene grain usually shows a similar extinction angle under optical microscopy unlike the olivine, probably preserving original crystal orientation. Alma3-1 is mainly composed of olivine, but small amounts of pyroxene (~5 vol.%) are present as veins with widths of up to 200 μm. Both olivine and pyroxene show granoblastic mosaic textures composed of 10-20 μm minute grains. At the boundary with the pyroxene area, pyroxene is present in the interstices of euhedral olivine grains. Pyroxene often shows twinning, probably on (100). The abundance of carbon phases and metal in Alma3-1 is smaller than that in Alma7, which would account for its whitish appearance.

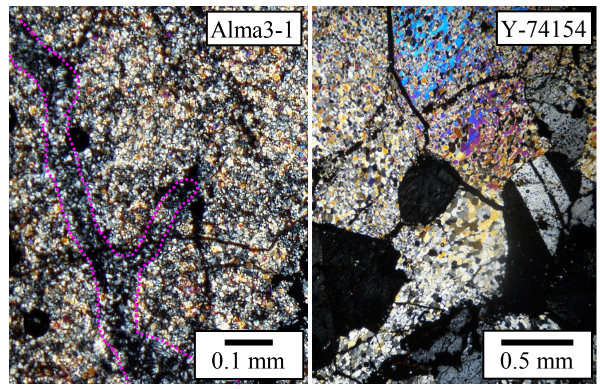


Fig. 1. Optical photomicrographs (cross polarized light) of Alma3-1 (left) and Y-74154 (right), both showing mosaicized texture. Pyroxene is present in the dashed area of Alma3-1. Note that Alma3-1 shows a finer-grained texture.

Mineral Chemistry: Electron microprobe analysis shows that pyroxenes in Alma are mostly low-Ca pyroxene with wide compositional ranges (Fig. 2). The low-Ca pyroxene in Alma7 shows chemical zoning both in Mg-Fe and Ca ($En_{90-80}Wo_{3-10}$) with the Fe-rich low-Ca pyroxene cores to the Mg-rich rims with higher Ca contents. Small amounts of augite (up to 5 μm, $En_{57}Wo_{40}$) are present associated with interstitial Si-rich phases (Fig. 3). Pyroxenes in Alma3-1 are clearly more Fe-rich ($En_{85-78}Wo_{2-6}$) than those in Alma7 (Fig. 2). In Alma3-1 pyroxene, Fe and Ca are positively correlated. Olivine in Alma3-1 is also more Fe-rich (Fa_{12-23}) than that in Alma7 (Fa_{3-18}) (Fig. 2). Both samples show small variation in Mg and Fe contents in the minute crystals, due to chemical zoning by reduction, but a millimeter scale heterogeneity is also present. Minor elements in olivine are 0.35-0.5 wt% MnO, 0.1-0.3 wt% CaO, and 0.25-0.6 wt% Cr_2O_3. The olivine mineralogy is described in more detail in [7].

Pyroxene Crystal Structure: The pyroxene crystal structure gives important information on thermal history when coupled with chemical composition. Thus we employed electron back-scatter diffraction (EBSD) on FEG-SEM and synchrotron X-ray diffraction (XRD) to study the crystallography of Alma pyroxenes. Although the Ca contents of low-Ca pyroxenes are as low as Wo_2, the obtained Kikuchi bands show that all low-Ca pyroxenes have the pigeonite ($P2_1/c$) crystal structure (Fig. 3). This is consistent with the observation that (100) twinning is common in these low-Ca pyroxenes. Alma7 pigeonites in the same pyroxene areas show generally similar orientation as suggested by optical microscopy. The Kikuchi bands from augite in Alma7 can be indexed by the $C2/c$ augite structure, but it is usually difficult to distinguish between the $P2_1/c$ and $C2/c$ pyroxene structures on EBSD patterns. SEM-EBSD was also performed on olivine, and Kikuchi bands from all grains analyzed could be indexed by the olivine structure and no high-pressure polymorph of olivine was found. The results by synchrotron XRD obtained at two Japanese synchrotron facilities (BL-4B1 at PF, KEK and BL37XU at SPring-8) will be given at the meeting.

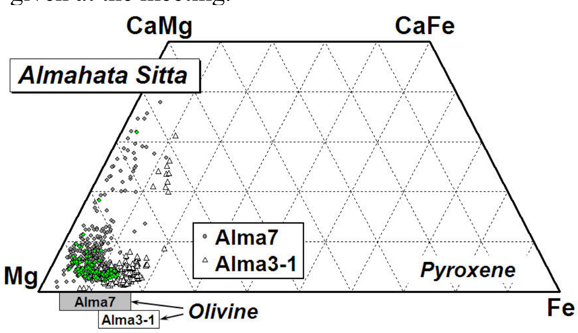


Fig. 2. Major element compositions of pyroxene (quadrilateral) and olivine (shown in two boxes under the quadrilateral) in Alma samples studied. Green circles on the pyroxene quadrilateral show compositions of pyroxenes in Fig. 3.

Discussion and Conclusion: Some ureilites are known to exhibit a mosaicized olivine texture similar to Alma, interpreted to result from shock at high temperature, possibly related to the breakup of the ureilite parent body [e.g., 4,5]. Although the abundance of diamond in Alma is small [1], Alma should have also suffered from shock metamorphism. As is observed in other mosaicized ureilites, the variation in pyroxene compositions in Alma may be due to cation migration during shock [8]. Even partial melting of silicates might occur since both olivine and pyroxene often show recrystallization textures with small amounts of interstitial Si, Al-rich phases (Fig. 3). The presence of such interstitial material is found in other ureilites [e.g., 9]. The Mg-Fe reverse zoning in Alma7 pyroxenes may suggest crystallization during reduction.

Although Alma displays high shock metamorphism textures overprinted by mosaicized olivine and deformed pigeonite, the pyroxene compositions are still useful to deduce their thermal history. The absence of orthopyroxene (*Pbca*) in Alma indicates that the pyroxene equilibration temperature was high, probably higher than 1300 °C [e.g., 9-11], which is similar to Asuka 881989 [12].

The pyroxene composition of Alma7 is similar to the most magnesian ureilites such as ALH82106 and NWA2236 [e.g., 9]. In contrast, silicate compositions of Alma3-1 are closer to the ferroan ureilites [e.g., 13]. Alma3-1 is especially similar to ALH81101 because of olivine and pyroxene polycrystalline textures and their compositions, although Alma3-1 displays a finer-grained texture [7]. They may share the same origin on the ureilite parent body. Our two samples represent clasts of two distinct ureilite members, and their coexistence of these two unique members in the same polymict ureilite indicates their genetical relationship on the same parent body [13].

References: [1] Jenniskens P. et al. (2009) *Nature, 458,* 485-488. [2] Herrin J. et al. (2009) *Meteoritics & Planet. Sci., 44,* 5444. [3] Takeda H. (1987) *Earth & Planet. Sci. Lett*., 81, 358-370. [4] Mittlefehldt D.W. (1998) *Rev. in Mineralogy, 36,* Chap. 4. [5] Goodrich C.A. (2004) *Chemie de Erde*, *64*, 283-327. [6] Berkley J. L. (1986) *Meteoritics*, *21*, 169-189. [7] Zolensky M. et al. (2010) *LPS XLI* (this volume). [8] Tribaudino M. (2006) *Meteoritics & Planet. Sci., 41,* 979-988. [9] Takeda H. et al. (1989) *Meteoritics*, *24*, 73-81. [10] Lindsley D. H. (1983) *American Mineral*., *68*, 477-93. [11] Takeda H. (1989) *Earth & Planet. Sci. Lett*., *93*, 181-194 [12] Takeda H. et al. (2009) *Meteoritics & Planet. Sci., 44,* 5117. [13] Downes H. et al. (2008) *Geochim. Cosmochim. Acta*, *72*, 4825-4844.

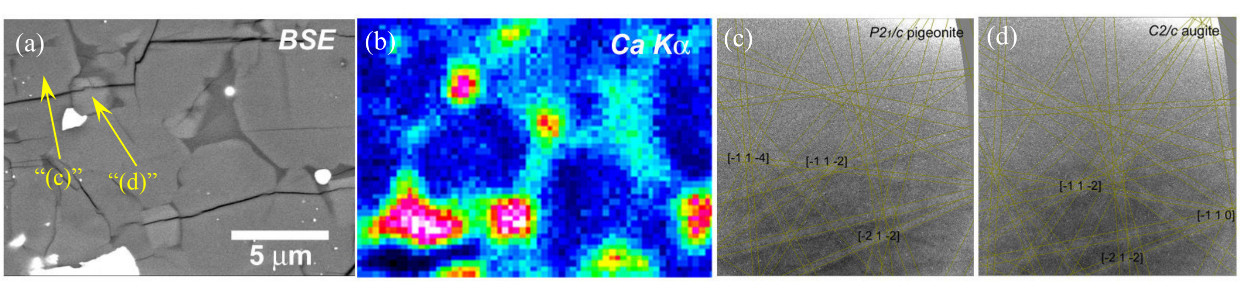


Fig. 3 (a) BSE image of pyroxene-rich area in Alma7. (b) Corresponding Ca X-ray map. Dark blue is Fe-rich low-Ca pyroxene. Bright blue is mostly Mg-rich pigeonite with high Ca content. Augite is pink to white. (c) Kikuchi bands of low-Ca pyroxene matching the pigeonite $P2_1/c$ structure. (d) Kikuchi bands of high-Ca pyroxene matching the augite $C2/c$ structure.

OXYGEN ISOTOPE COMPOSITION OF ALMAHATA SITTA. D. Rumble[1], M. E. Zolensky[2], J. M. Friedrich[3], P Jenniskens[4], and M. H. Shaddad[5], [1]Geophysical Laboratory, Carnegie Institution, Washington, DC 20015 (rumble@gl.ciw.edu), [2]NASA Johnson Space Flight Center, 2101 NASA Parkway, Houston, TX 77058, [3]Department of Chemistry, Fordham University, 441 East Fordham Road, Bronx, NY 10458, [4]Carl Sagan Center, SETI Institute, 515 North Whisman Road, Mountain View, CA 94043, [5]Department of Physics, University of Khartoum, P. O. Box 321, Khartoum 11115, Sudan.

Introduction: The name "Almahata Sitta" 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 the Asteroid 2008 TC_3 [1]. Fragments of the meteorite were collected in December 2008 and March 2009, 2 to 5 months after the asteroid exploded in Earth's atmosphere on 7 October 2008.

Method: Eleven fragments of the meteorite have been analyzed for oxygen isotopes with a MAT 252 mass spectrometer using oxygen generated by heating 2-3 mg samples with a CO_2 laser in an atmosphere of BrF_5 under a pressure of 25 torr. Whole rock samples were crushed with a boron nitride mortar and pestle, ultrasonicated in dilute HCl for 5 minute, washed in de-ionized distilled water, and dried prior to analysis.

Results: 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 CCAM line as monomict and polymict members of the ureilite family of meteorites, as found in the classic work of Clayton & Mayeda [2], (Fig. 1).

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). These four samples, together with #47, show a limited variation in $\Delta^{17}O$, from -1.07 to -0.91 ‰. Franchi [3] observed sub-groups 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 sub-group. This subgroup may delineate the most abundant clasts in Almahata Sitta but with only 11 fragments analyzed of some 300 recovered stones a representative sampling has probably not been acquired as yet.

The group of Almahata Sitta samples defined by $-1.07 < \Delta^{17}O < -0.91$ resemble the type II clasts of Kita et al. [4] and the "Hughes cluster" of Downes et al [5] in that the groups share the same range of $\Delta^{17}O$ values. The significance of grouping by $\Delta^{17}O$ values in the case of ureilites is unknown because the members of the groups so defined differ in some aspects of mineral assemblage and mineral composition from Almahata Sitta.

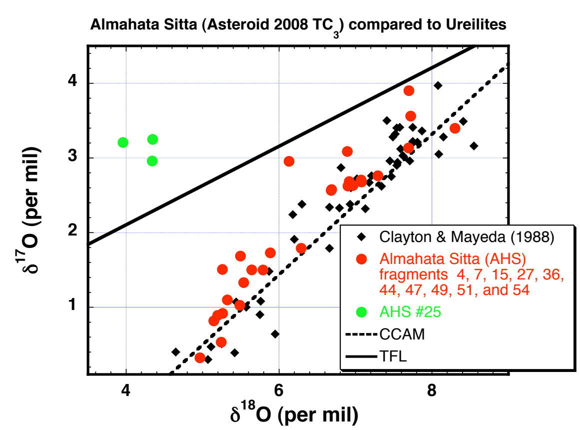
Fragment #25 has the oxygen isotope composition of an "H5" ordinary chondrite (Fig. 1). It has been identified petrographically as an "H5" ordinary chondrite and is unrelated to the ureilite Almahata Sitta.

Work is in progress to investigate a possible correlation between the mg# of olivine and pyroxene and their $\Delta^{17}O$ values [2,4,5].

Conclusions: It is now demonstrated beyond doubt that a single asteroidal body, Asteroid 2008 TC_3, contained clasts representative in their oxygen isotope compositions of all known ureilite monomict and polymict ureilites. The fragments of Almahata Sitta scattered in a line across the Nubian Desert afford researchers the puzzle pieces needed to reconstruct the ureilite's parent body. Might all of the ureilites in their manifold heterogeneity have originated on the same parent body? Yes, and the samples are in hand to prove it.

References: [1] Jenniskens, P. and 34 co-authors (2009) *Nature, 458,* 485-488. [2] Clayton R.N. and Mayeda, T. (1988) *GCA, 52*, 1313-1318. [3] Franchi, I.A. (2008) *Revs. Mineral. Geochem., 68*, 345-397. [4] Kita, N.T. and 5 co-authors (2004) *GCA, 68*, 4213-4235. [5] Downes, H. and 3 co-authors (2008) *GCA, 72*, 4825-4844.

Figure 1: *Oxygen isotope compositions of fragments of Almahata Sitta compared to ureilites [1], [2]. Note that AHS #25 is an H5 ordinary chondrite, unrelated to Almahata Sitta .*



CHROMIUM ISOTOPIC COMPOSITION OF ALMAHATA SITTA. L. Qin[1], D. Rumble[2], C. M. O'D. Alexander[1], R. W. Carlson[1], P. Jenniskens[3], and M. H. Shaddad[4]. [1]Department of Terrestrial Magnetism, and [2]Geophysical Laboratory, Carnegie Institution of Washington, Washington, DC 20015, USA. [3]Carl Sagan Center, SETI Institute, 515 North Whisman Road, Mountain View, CA 94043, USA [4]Department of Physics, University of Khartoum, P. O. Box 321, Khartoum 11115, Sudan. (E-mail: lqin@ciw.edu)

Introduction: Ureilites are a unique group of achondrites. They are composed mostly of olivine and pigeonite with igneous textures. However they also have some features that make them appear "primitive"[1]. In a 3-oxygen-isotope plot ($\delta^{17}O$ vs. $\delta^{18}O$), ureilites plot on the upper 1/3 of the CCAM (carbonaceous chondrite anhydrous minerals) mixing line [2]. Thus, a carbonaceous chondrite precursor material has been suggested for these meteorites [3]. However, ureilites exhibit considerable variation along the CCAM line (making it difficult to pair them with any particular carbonaceous chondrite). Studies have suggested that Cr isotopic compositions can be used as a fingerprint for meteorite classification (e.g. [4-7]). This is because different types of chondrites and achondrites show distinct $^{54}Cr/^{52}Cr$ ratios. In particular, carbonaceous chondrites show positive ^{54}Cr anomalies of up to 2ε (relative deviation of the isotope ratio from a terrestrial standard times 10000), and ordinary chondrites show uniform negative anomalies of ~ -0.4ε. Thus Cr isotope composition is a promising tool to test the genetic link between ureilites and chondrites.

The recent ureilite fall Almahata Sitta is comprised of hundreds of stones that were recovered from the Nubian Desert coincident with the projected Earth-impacting orbit of the Asteroid 2008 TC_3 [8]. Oxygen isotope data for this sample cover the entire range previously observed for ureilites of both monomict and polymict classes (Rumble et al. this volume). The heterogeneity in O isotope compositions of this meteorite makes it ideal for studying the correlation between $\Delta^{17}O$ and $\varepsilon^{54}Cr$ displayed by carbonaceous chondrites [6]. Another advantage of studying Cr isotopic composition is that ^{53}Cr is the decay product of ^{53}Mn, an extinct nuclide with a half time of 3.7 Ma. It can thus potentially provide age constraints on this meteorite if it formed before ^{53}Mn decay ceased.

Methods: Eight samples of Almahata Sitta were studied for Cr isotopic composition. Only the non-magnetic fractions of the samples were studied, except for one sample in which both the magnetic and non-magnetic portions were analyzed. About 5 mg of fine chips pre-treated with diluted HCl was dissolved with a concentrated HNO_3/HF mixture. All materials went into solution except for some dark residue. Raman spectra revealed that these residues are mostly graphite.

Chemical separation of the Cr followed the method described in [7], and Cr isotopic compositions were measured on a Triton thermal ionization mass spectrometer at DTM. Each sample and the terrestrial laboratory standard were analyzed at least 6 times. Each run consisted of 420 ratios, with each ratio integrating ion intensity for 8 seconds. Only the average of the Cr isotope ratios from all the runs are reported here.

Results and Discussions: The Cr isotopic compositions of the non-magnetic fractions of the samples are shown in Fig. 1. All samples essentially have the same $\varepsilon^{54}Cr$ within error, averaging at -0.75. This value is distinctive from the positive anomalies observed in carbonaceous chondrites (Fig. 1.). However, it is equal to the values measured for eucrites and diogenites [5]. This indicates that Almahata Sitta was derived from a parent body that has a similar Cr isotopic composition to the HED parent body. It is noted that so far all the achondrites analyzed show negative $\varepsilon^{54}Cr$ anomalies. The magnetic portion of one sample shows a $\varepsilon^{54}Cr$ value of -1.86±0.20, which is significantly lower than the values for the non-magnetic fractions. It has an $\varepsilon^{53}Cr$ value of 0.35±0.14, similar to the non-magnetic portion of the sample. Thus the lower $\varepsilon^{54}Cr$ value of the magnetic fraction is not likely to be caused by mass fractionation, as this would have been reflected in a lower value of $\varepsilon^{53}Cr$. Little is known about the difference in the mineralogy between the non-magnetic and magnetic fractions of the sample except that the latter contains most of the metal. The more negative $\varepsilon^{54}Cr$ value in the magnetic fraction might reflect the Cr isotope signature in the impactor that disrupted the ureilite parent body. But no previously analyzed meteorite type has $\varepsilon^{54}Cr$ this low. Further constraints on the cause of the Cr isotope heterogeneity in Almahata Sitta require the analyses on the magnetic fractions of more Almahata Sitta samples, along with a thorough study on the mineralogy in the magnetic-fraction.

The $\varepsilon^{53}Cr$ values in the non-magnetic fractions range from 0.15±0.03 to 0.34±0.04. The total variation of 0.2ε is resolvable with our analytical precision, indicating live ^{53}Mn at the last Cr isotope equilibrium in

Almahata Sitta meteorite. Mn/Cr ratios will be determined to constrain the age of this event.

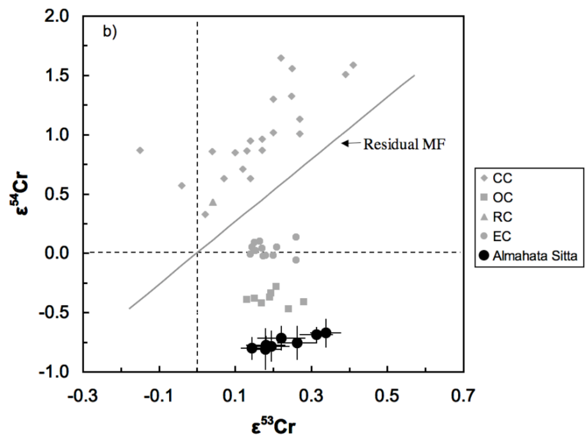


Fig. 1. Cr isotopic composition of Almahata Sitta and chondrites. The chondrite data are from [7].

A positive correlation of ε^{54}Cr with Δ^{17}O has been suggested for carbonaceous chondrites (e.g. [5, 9]). Because the variations in Δ^{17}O are thought to result from photodissociation, and variations in ε^{54}Cr are conventionally believed to be nucleosynthetic in origin, the apparent correlation between the two was used to question the photodissociation explanation for the O isotope variations in carbonaceous chondrites. Fig. 2 shows that ε^{54}Cr does not correlate with Δ^{17}O in Almahata Sitta. This implies that the process that governed the distribution of the ^{54}Cr carrier may not be responsible for the O isotope heterogeneity in the Solar System. This is consistent with the lack of correlation in the inner Solar System materials [7].

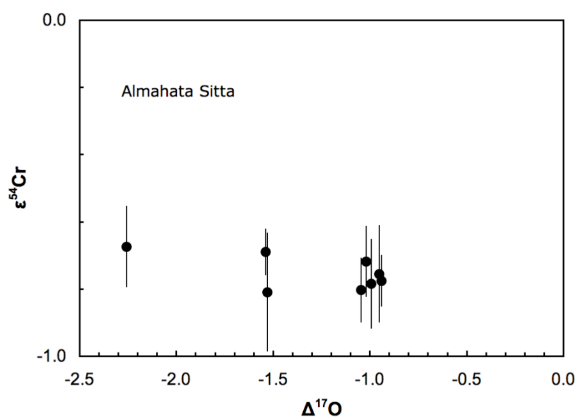


Fig. 2. ε^{54}Cr vs. Δ^{17}O for Almahata Sitta.

Conclusions: The Cr isotope compositions of Almahata Sitta samples suggest that this meteorite is derived from a parent body that is different from that of known carbonaceous chondrites, contradicting what has been suggested based on O isotopic compositions. Almahata Sitta has a similar ε^{54}Cr value to that of the HED parent body. We note that so far all the achondrites that have been analyzed all display negative ε^{54}Cr anomalies. The lack of a correlation between ε^{54}Cr and Δ^{17}O suggests that the process that has governed the O isotope heterogeneity may not be responsible for the heterogeneity of Cr isotopic composition. Variations of ε^{53}Cr likely reflect live ^{53}Mn at the time of the last isotopic equilibration.

References: [1] Goodrich C. A. et al. (2001) *GCA, 65,* 621-652. [2] Clayton R. N. and Mayeda, T. (1988) *GCA, 52,* 1313-1318. [3] Kita N. T. et al. (2004) *GCA, 68*, 4213-4235. [4] Shukolyukov A. and Lugmair G. W. *ESPL, 250*, 200-213. [5] Trinquier A. et al. (2007) *ApJ, 655*, 1179-1185. [6] Trinquier A. et al. (2008) *GCA*, 72, A956. [7] Qin L. et al. *GCA,* In press. [8] Jenniskens P. et al. (2009) *Nature, 458*, 485-488. [9] Yin Q.-Z. (2009) *LPS XXXX*, Abstract #2006.

INFRARED SPECTROSCOPY OF SAMPLES FROM MULTIPLE STONES FROM THE ALMAHATA SITTA METEORITE.

S. A. Sandford,[1] S. N. Milam,[1,2] M. Nuevo,[1] P. Jenniskens,[2] and M. H. Shaddad[3]. [1]Astrophysics Branch, NASA-Ames Research Center, Moffett Field, CA 94035 USA, [2]SETI Institute, Mountain View, CA 94043 USA, [3]Department of Physics, University of Khartoum, Sudan.

Introduction: On 7 October 2008, the asteroid 2008 TC3 entered the Earth's atmosphere, exploded at 37km altitude, and created a strewn field of stones, now known as the Almahata Sitta meteorite, in the Sudan desert. Preliminary analysis of one of these stones showed it to be a unique polymict ureilite [1]. Here we report on 39 mid-infrared transmission spectra taken from 26 different stones collected from the strewn field.

Samples and Measurement Techniques: Because the total available material for most of the stones examined were small, only limited samples were available for this study. Typical sample sizes obtained were in the 5–10 mg range, although a few were smaller due to lack of available material. In many cases a spectrum was measured from only a single sample from a particular stone. In other cases enough material was available from a stone to make multiple samples and measurements. Care was taken to ensure that selected samples were free from contaminants and fusion crust.

The material in most of the meteorites consisted of a dark, porous/friable matrix, often with visible embedded crystals. The crystals were generally sub-mm in size, although larger crystals were occasionally seen. The samples from most stones looked qualitatively similar and wherever possible an attempt was made to select and use samples that were representative of the material available from each stone.

It is worth noting that the olivine-pigeonite aggregates in ureilites are typically 0.1–2.0 mm in diameter (see [2]), but domains as large as 7 mm have been reported. While the material in Almahata Sitta #7 is anomalously fine-grained, this was not true for all the stones from which samples were obtained. Some samples contained larger individual mineral grains in the matrix. Thus, there exists the possibility that some of the samples described here could be dominated by local heterogeneities and therefore fail to be representative of the original stone as a whole. Where possible, we have prepared and measured multiple samples from the same stone to help assess the extent of this issue.

The samples were prepared using the standard KBr pellet techniques described in Sandford [3]. In general, samples of a few mg were mixed with 100 times their mass of KBr and then ground mechanically for 2 minutes in an all-steel ball mill. Approximately 100 mg of the resulting powder was then compress in a 1.5 cm diameter die at 1.1 × 10^8 Pa for 1 minute to make a thin pellet suitable for IR transmission measurements. The resulting variability in sample density and column depth between the various meteorite sample pellets is expected to be on the order of 1%.

IR spectra were taken using a Bio-Rad Excalibur Fourier transform infrared spectrometer equipped with a Globar source, a KBr beamsplitter, and a liquid nitrogen-cooled mercury-cadmium-telluride detector. Spectral from 7000 to 450 cm^{-1} (1.43–22.2 µm) were measured at a resolution of 1 cm^{-1}, which is more than adequate to resolve mid-IR mineral bands. It was generally possible to obtain spectra with signal-to-noise ratios of ~0.2% in a modest number of scans. The number of scans used was therefore usually determined by selecting a scan time that provided good cancellation of atmospheric H_2O and CO_2 bands by the background spectrum. No additional corrections for telluric gases were made to the spectra.

Results: The ureilite spectra show a number of absorption bands including a complex feature centered near 1000 cm^{-1} (10 µm) due to Si–O stretching vibrations (Figures 1-3). The profiles of the silicate features fall along a mixing line with endmembers represented by Mg-rich olivines and pyroxenes, and no evidence is seen for the presence of phyllosilicates. The relative

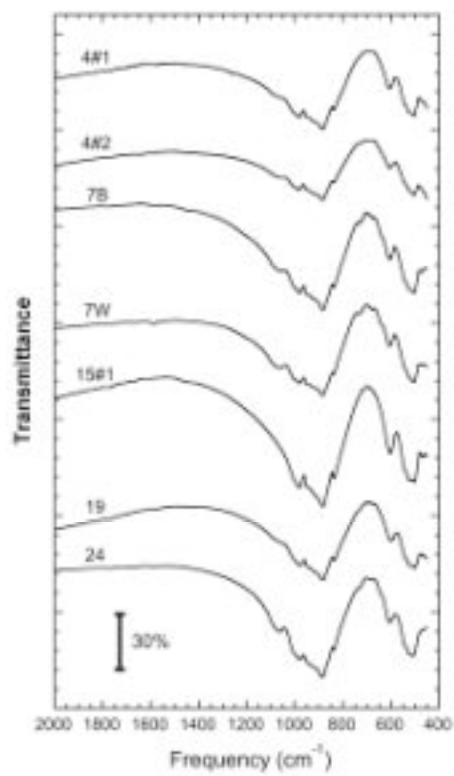


Figure 1: IR spectra from 2000 to 450 cm^{-1} (5.0–22.2 µm) of some of the olivine-rich samples of Almahata Sitta.

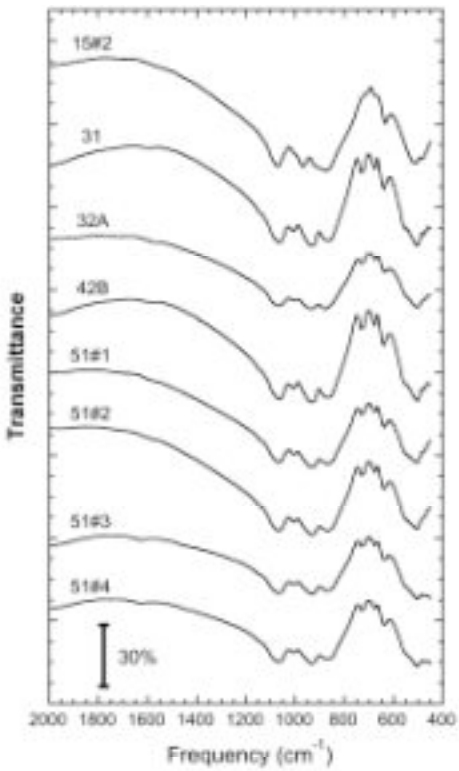


Figure 2: IR spectra from 2000 to 450 cm^{-1} (5.0–22.2 µm) of pyroxene-rich samples of Almahata Sitta. The spectrum of sample 15#2 is unique and matches that of enstatite.

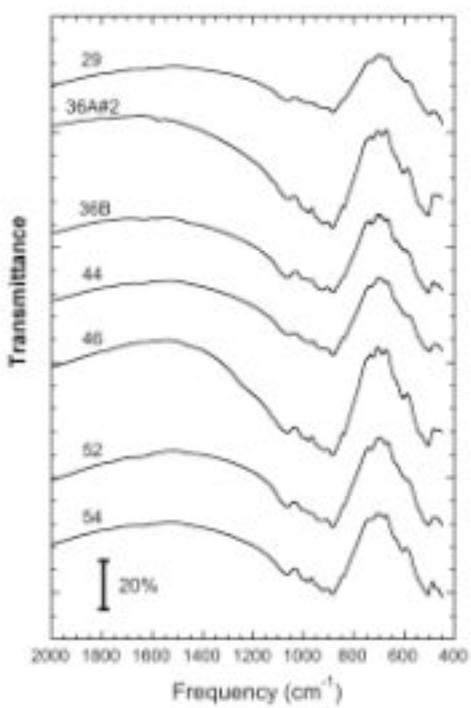


Figure 3: IR spectra from 2000 to 450 cm^{-1} (5.0–22.2 µm) of samples of Almahata Sitta that show mixtures of olivines and pyroxenes.

abundances of olivine and pyroxene show substantial variation from sample to sample and sometimes differ between multiple samples taken from the same stone. Analysis of a mass-normalized coaddition of all our ureilite spectra yields an olivine:pyroxene ratio of 74:26, a value that falls in the middle of the range inferred from the infrared spectra of other ureilites. Both the predominance of olivine and the variable olivine-to-pyroxene ratio are consistent with the known composition and heterogeneity of other ureilites.

The precise positions of the principle absorption bands of olivine provide a measure of the Mg/Fe ratio in the mineral. Comparison of the peak positions of the olivine bands in the Almahata Sitta spectra with those from mineral standards indicate the olivines are very Mg-rich, consistent with the known mafic nature of this mineral in ureilites. With one exception (15#2), the spectra dominated by pyroxene are consistent with an assignment to pigeonite, in agreement with the mineralogy of many ureilites and Almahata Sitta stone #7. One unique sample, 15#2, yielded a pyroxene spectrum most consistent with assignment to enstatite.

Variations in the colors of the KBr pellets and the intensities of the silicate feature relative to sample mass indicate a significant contribution from additional materials having no strong absorption bands, most likely graphitized carbon, diamonds, and/or metal.

Conclusions: We have obtained 39 mid-infrared (4000–450 cm^{-1}; 2.5–22.2 µm) transmission spectra taken from 26 different stones from the Almahata Sitta meteorite. The strongest absorption in the spectra consist of a complex feature centered near 1000 cm^{-1} (10 µm) attributed to Si–O stretching vibrations in silicates. The profile of the silicate feature varies from sample to sample; all the spectra are dominated by mixtures of olivines and pyroxenes. Mixtures span the entire range from nearly pure olivine to nearly pure pyroxene. The mass weighted average spectrum of all the ureilite samples yields an olivine:pyroxene ratio of 74:26, which falls in the middle of the range reported for other ureilites. The predominance of olivine and the variable olivine-to-pyroxene ratio (both within and between stones) are consistent with the known composition and heterogeneity of other ureilites.

Variations in the intrinsic strength of the silicate feature and its surrounding infrared continuum indicate the variable presence of material with no strong infrared absorption bands. The most likely candidate for this infrared-neutral material is graphitized carbon, but diamond and metals could contribute.

A more detailed description of these results has been submitted to *MAPS* [4].

References: [1] Jenniskens P., et al., 2009, *Nature* 458:485–488. [2] Berkley J. L., 1986, *Meteoritics* 21:169–189. [3] Sandford, S. A., 1993, *Meteoritics* 28:579-585. [4] Sandford, S. A., et al., *MAPS*, submitted.

Tuesday, March 2, 2010
POSTER SESSION I: UREILITES
7:00 p.m. Town Center Exhibit Area

Karczemska A. Jakubowski T.
Raman Imaging of Ureilitic Diamonds **[#1639]**
We performed Raman Imaging of diamonds from three ureilitic samples. Results show the coexistence of several diamond types based on the various observed shift positions in the studied ureilites.

Ash R. D. Goodrich C. A. Van Orman J. A. McDonough W. F.
Petrography and Siderophile Geochemistry of Metal and Sulphide in Ureilites **[#1302]**
We have measured highly siderophile elements in sulphides and metals in well characterised olivine-low Ca pyroxene ureilites with a range of petrogenetic characteristics. Metals are the dominant carriers of PGEs, but Pd may be affected by sulphides.

Ross A. J. Downes H. Smith C. L. Jones A. P.
DaG 1047: A Polymict Ureilite Containing Exotic Clasts Including a Chondrite **[#2361]**
We present EPMA data for the polymict ureilite DaG 1047. This meteorite contains multiple exotic clasts not found in monomict ureilites such as feldspars, Si-bearing metals (suessite) and a chondritic clast containing well-preserved chondrules.

Goodrich C. A.
Late Orthopyroxene + Metal Assemblages in Ureilites, Brachinites, and Other Olivine-rich Achondrites **[#1091]**
Fine-grained assemblages of orthopyroxene + metal in some brachinites and related olivine-rich achondrites may have formed by late reduction, similar to ureilites.

Warren P. H.
Ureilites: Pigeonite Thermometry and the Unimportance of Pressure-buffered Smelting During Evolution as Asteroidal Mantle Restites **[#1530]**
Ureilite equilibration T derived from pigeonite composition shows a strong (+) correlation with olivine Fo. Combinations of T and Fo implicit in combinations of P and Fo proposed for P-buffered smelting match real ureilite data very poorly.

Bischoff A. Horstmann M. Laubenstein M. Haberer S.
Asteroid 2008 TC3 — Almahata Sitta: Not Only a Ureilitic Meteorite, but a Breccia Containing Many Different Achondritic and Chondritic Lithologies **[#1763]**
Meteorite Almahata Sitta has been classified as a polymict ureilite. We have studied more than 30 fragments from the strewn field and found that Almahata Sitta is a complex mixture of ureilitic and chondritic lithologies.

Horstmann M. Bischoff A.
Characterization of Spectacular Lithologies from the Almahata Sitta Breccia **[#1784]**
Meteorite Almahata Sitta has been classified as a polymict ureilite, but it contains a huge number of spectacular fragments of different ureilitic and chondritic lithologies.

Zolensky M. E. Herrin J. Mikouchi T. Satake W. Kurihara T. Sandford S. A. Milam S. N. Hagiya K. Ohsumi K. Friedrich J. M. Jenniskens P. Shaddad M. H. Le L. Robinson G. A.
Olivine in Almahata Sitta — Curiouser and Curiouser **[#2306]**
Description of olivine in the Almahata Sitta urilite.

Hoffmann V. H. Hochleitner R. Torii M. Funaki M. Mikouchi T. Almahata Sitta Consortium
Magnetism and Mineralogy of Almahata Sitta **[#2120]**
The aims of our investigations are unrevealing Almahata Sitta’s (AS) magnetic signature, phase composition and mineralogy (main focus on the opaques) and getting new insights to the ureilite parent body magnetism (2008TC3 belongs to F-type asteroids).

Ott U. Herrmann S. Jenniskens P. M. Shaddad M.
A Noble Gas Study of Two Stones from the Almahata Sitta Meteorite **[#1195]**
Noble gases analyzed in two stones from the Almahata Sitta polymict ureilite indicate a cosmic ray exposure age of ~12.5 Ma. No evidence is seen for implanted solar wind, while heavy primordial noble gases show a typical ureilite pattern.

Hiroi T. Jenniskens P. M. Bishop J. L. Shatir T.
Reflectance Spectroscopy of Almahata Sitta Meteorite Samples from Asteroid 2008 TC3 **[#1148]**
As a preliminary study, the visible-NIR reflectance spectra of chip and powder samples of select stones of Almataha Sitta meteorite have been measured to provide insights into the surface and internal compositions and possibly the surface physical properties of 2008 TC_3.