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]Affilia [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: Prior to recovery the Almahata Sitta fall was observed as the asteroid 2008 TC3 on an Earth-bound trajectory, providing a unique link between spectral data and ureilite composition. The event has also provided insight into the nature of ureilitic objects in space. In particular, the large size (4 m^3) and low density (2.2 g/cm^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, then use this information to compare the inferred size of fragments within the asteroid to those initially dislodged from a common ureilite patrent body (UPB).

Methods: Polished specimens were prepared from six different recovered fragments of Almahata Sitta (1, 4, 15, 25, 47, 75). EPMA measurements of silicate mineral compositions were performed 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 Element2XR mass spectrometer.

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 less compatible 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 [8].

Stage 2: Disruption of hot UPB mantle. A favored topic in ureilite petrology is the catastrophic disruption of the UPB, a large (>200km diameter [13]) asteroid that existed in the early solar system [e.g. 4]. Converging lines of evidence reveal that the UPB mantle underwent massive fragmentation while still hot [13]. In Almahata Sitta, two-pyroxene equilibrium temperatures [14] 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 (Sample 1) 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 [5], 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 disequlibrium in olivine and pyroxene from Almahata Sitta to estimate minimum cooling rates using the asymptotic cooling model of [6] shown below.

cooling constant for asymptotic model

diffusion coefficient at initial temperature $\log D(\text{Fe-Mg}) = -5.54 + 2.6X_{Fe} - (12530/T)$ [6,9]

$$\frac{\partial T}{\partial t} = -\eta T^2 = \frac{64 D(T_o) R T}{Q X_T^2}$$

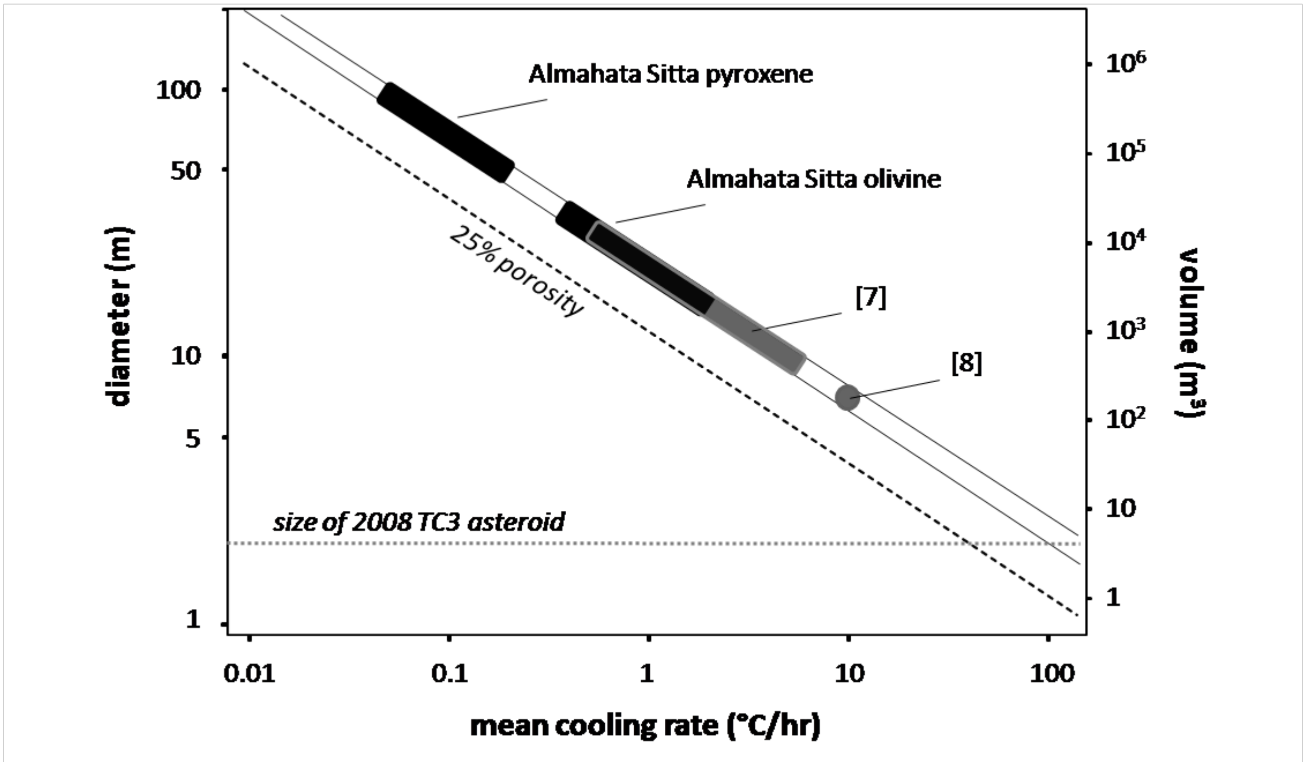
cooling rate

activation energy Q = 240 kJ/mol [6,9]

diffusion distance

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 [7,8].

Stage 4: Cold re-accretion. Sometime after the aforementioned catastrophy, fragments of the UPB mantle re-accreted into smaller daughter asteroids with insufficient latent or radiogenic heat to exceed silicate 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 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 fall area that may or may not be paired. 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 regolith. To compare fragmentation resulting from catastrophic disruption of the UPB and fragment size within 2008 TC3, we estimated the initial size of 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. Over a range of relevant thermal diffisivity from 5e-7 [15] to 6.3e-7 [12] and 2e-7 for highly porous media [11], mean cooling rates inferred from ureilite mineral rims would be experienced by spherical bodies 10-100 m in diameter. By contrast, fragments that comprised asteroid TC3 were likely on the order of centimeters to tens-of-centimeters and thus much smaller than typical fragments initially dislodged from hot UPB mantle. Subsequent fragmentation, either prior to or after accretion of daughter asteroids, must have occurred by a process that did not result in mixing of 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 methods. Future work might incorporate mass balance of phases and diffusion of minor elements in order to better constrain initial zoning profiles and cooling rates.

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