COORDINATED STUDIES OF SAMPLES RELEVANT FOR CARBONACEOUS ASTEROID SAMPLE RETURN: CM CHONDRITES AGUAS ZARCAS AND METEORITE HILLS 00639. J. Davidson[1], C. M. O'D. Alexander[2], H. C. Bates[3], A. J. King[3,4], D. I. Foustoukos[2], D. L. Schrader[1], E. S. Bullock[2], R. C. Greenwood[4], H. Busemann[5], P. Morino[5], M. E. I. Riebe[5], M. Rüfenacht[5], M. Schönbächler[5], and P. Clay[6]. [1]Center for Meteorite Studies, Arizona State University, 781 East Terrace Road, Tempe, AZ 85287-6004, USA (jdavidson@asu.edu). [2]Carnegie Institution for Science, 5241 Broad Branch Road, Washington, DC 20015, USA. [3]Department of Earth Science, Natural History Museum (London), Cromwell Road, London SW7 5BD, UK. [4]Department of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK. [5]Institute of Geochemistry and Petrology, ETH Zürich, CH-8092 Zürich, Switzerland. [6]School of Earth and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, M13 9PL, UK.

Introduction: With both NASA and JAXA due to return samples from carbonaceous asteroids within the next four years, studies of analogous carbonaceous chondrites are of critical importance to support the analysis of these future returned samples. JAXA's Hayabusa2 will return samples from asteroid Ryugu, a C-type asteroid, in December 2020 while NASA's OSIRIS-REx will return samples from asteroid Bennu, a B-type asteroid, in September 2023. Spectroscopic observations of these asteroids compared to laboratory measurements of meteorites suggest Ryugu is most consistent with heated CI and heated CM chondrites [1, 2] while Bennu is most consistent with CM chondrites (although a relationship to heated CM [3] or CI chondrites [4] is also possible).

We report the preliminary results of detailed coordinated studies of the recent fall Aguas Zarcas (CM2) and the Antarctic find Meteorite Hills (MET) 00639 (shock-heated CM2), which may be petrologically similar to material returned from asteroids Bennu and Ryugu, respectively. The study of analogous material prior to sample return will increase the scientific value of returned samples and constrain the formation and alteration conditions of their parent asteroids.

Samples: The CM breccia Aguas Zarcas fell in Costa Rica on the 23rd April 2019 (27 kg total mass) [5]. We report preliminary data from four samples (including polished sections and powdered chips of each), two of which were collected prior to rain and two of which were collected after several days of rain for comparison. The brecciated Antarctic find MET 00639 (13.4 g total mass) is part of a larger CM pairing group that exhibits platy or shale-like matrix [6] and has been identified as a close spectral match to asteroid Ryugu [2]. We report data from MET 00639 split 7 (thin section) and split 19 (500 mg chip).

Analytical Methods: Chips of all five samples (four Aguas Zarcas, one MET 00639) were crushed to a grain size of <40 μm and were well-homogenized. Aliquots were analyzed for bulk H, C and N according to the method of [7] at the Carnegie Institution for Science, and for bulk O isotopes according to the method of [8] at the Open University. Bulk Ti and Cr isotopes and noble gases [9] were analyzed at ETH Zurich. Bulk mineralogy was determined via position sensitive detector X-ray diffraction (PSD-XRD) at the Natural History Museum in London (e.g., [10, 11]). Near-infrared (NIR) and mid-infrared (MIR) reflectance spectra were collected with a Fourier Transform Infrared (FTIR) spectrometer at the University of Oxford. Backscattered electron (BSE) images and X-ray element maps were obtained on polished sections using a Cameca SX-100 electron probe microanalyzer (EPMA) at the University of Arizona's Lunar and Planetary Laboratory (LPL). Element maps were used to identify mineral phases for quantitative analysis, which were then imaged in high resolution using the JEOL JXA-8530F Hyperprobe field emission EPMA at Arizona State University (ASU) (operating conditions: 20 kV and 15 nA). Quantitative compositional analyses (silicate and opaque phases) were subsequently performed on the Cameca SX-100 EPMA using similar conditions to those reported in [12].

Results and Discussion (Aguas Zarcas):

Bulk isotopes (H-C-N-O-Ti-Cr). Bulk O, Ti and Cr isotope compositions indicate all Aguas Zarcas samples analyzed here are consistent with a CM classification. The three samples analyzed for O isotopes to date have a range of $\delta^{18}O$ values of 7.4 to 8.8 ‰; intermediate between the values reported by [5] and [13]. Bulk H-C-N abundances and isotope compositions indicate that Aguas Zarcas is slightly heated and a petrologic type 1.4–1.6 on the scale of [14].

Bulk spectral characteristics (IR). The IR spectra for two of the Aguas Zarcas samples are consistent with intermediate to highly aqueously altered CM chondrites (i.e., CM1/2 to CM1). Their 3 μm features are similar to those of the group 2 spectra in [15]. A third sample appears to be less aqueously altered, more consistent with CM2 spectra.

Bulk mineralogy (PSD-XRD). The main crystalline phases identified in the bulk Aguas Zarcas samples include olivine, pyroxene, magnetite, Fe-sulfide (pyrrhotite and pentlandite) and calcite. The total phyllosilicate (secondary alteration minerals including Mg-serpentine and Fe-cronstedtite) abundance provides a

measure of the degree of aqueous alteration experienced in a sample's parent body (e.g., [10, 11]). The abundances of phyllosilicates (~74 to 85 vol.%) and minor phases vary between the lithologies. Data indicate that the four Aguas Zarcas samples are intermediately aqueously altered CM chondrites, with petrologic types CM 1.3 to 1.5 according to the scheme of [11], equivalent to 2.2 to 2.4 on the scale of [16]. No evidence of heating was observed.

Noble gases. Noble gas data vary between lithologies but are consistent with CM chondrites. No evidence for solar wind implantation was observed.

Petrography. Petrographic observations suggest that the four Aguas Zarcas samples represent three different lithologies. Fine-grained chondrule rims and phyllosilicates are common in each lithology, though the extent and morphologies of alteration products vary. One lithology is particularly rich in tochilinite. Minor amounts of metal, predominantly Ni-poor, are present in all lithologies and are also detectable via PSD-XRD. Magnetite is more abundant than metal and sulfide combined. The sulfides in all Aguas Zarcas lithologies are compositionally consistent with low-temperature aqueous formation. The compositions of chrome-rich spinel vary significantly between lithologies, though this may be due to sampling bias. Chrome-spinel morphologies are generally euhedral, indicating that these samples are not significantly thermally metamorphosed (e.g., [17]). The average Cr-contents of ferroan olivine vary between lithologies, suggesting that they may have experienced different degrees of thermal metamorphism (e.g., [18]).

Results and Discussion (MET 00639):

Bulk isotopes (H-C-N). Bulk H data indicate that MET 00639 is moderately heated, somewhere between MET 01072 and MacAlpine Hills (MAC) 88100 (see [14]). O-isotope data are forthcoming.

Bulk spectral characteristics (IR). The IR spectrum for MET 00639 indicates that this sample has been highly aqueously altered. Its 3 μm feature is consistent with group 1 in [15], and resembles CM1 chondrites in [19]. However, the 3 μm feature is very shallow, possibly resulting from dehydration.

Bulk mineralogy (PSD-XRD). MET 00639 contains ~83 vol.% phyllosilicates and ~12 vol.% anhydrous silicates indicating that it is a highly aqueously altered CM1.3 according to the scheme of [11]. Furthermore, the intensities of the Fe-cronstedtite peaks in the XRD pattern of MET 00639 are lower than for typical CM chondrites, which could reflect a difference in crystallinity due to partial dehydration (in agreement with IR data).

Noble gases. Data are consistent with other CM chondrites. No evidence for solar wind was observed.

Petrography. MET 00639 exhibits highly variable alteration, with some regions consisting almost entirely of phyllosilicates while others have almost no phyllosilicates. The overall phyllosilicate abundance determined from the thin section (~80 vol.%) is consistent with that determined via PSD-XRD. Chondrules, including FeO-rich and FeO-poor chondrules, are predominantly <500 μm in diameter and commonly possess fine-grained rims. Some chondrules have undergone pseudomorphic replacement of their silicates. Iron metal is very rare (<<0.5 vol.%) and exclusively Ni-poor (<7 wt.% Ni). Iron-bearing hydroxide minerals are more abundant and commonly Ni-bearing. Chrome-spinel is subhedral to euhedral, indicating MET 00639 did not experience significant thermal metamorphism (e.g., [17]). All sulfides are compositionally consistent with low-temperature aqueous formation (i.e., pyrrhotite has low Fe/S ratios), regardless of the degree of aqueous alteration experienced locally in the thin section. Sulfides in MET 00639 are consistent with sulfides in the CM1/2 Allan Hills (ALH) 83100 [20].

Summary: This multi-technique petrographic–isotopic–spectroscopic–noble gas study suggests that the different lithologies within Aguas Zarcas likely experienced variable degrees of aqueous alteration and possibly minor thermal metamorphism on the meteorite's parent body (petrologic types ~1.3 to ~1.6). All data thus far indicate that MET 00639 is moderately heated, of petrologic type ~1.3, and more aqueously altered than Aguas Zarcas. The study of these analogous samples will help increase the scientific value of samples that will be returned from Bennu and Ryugu.

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