BRECCIATION OF CM CHONDRITES: COLD BOKKEVELD. M. Zolensky[1], M. Velbel[2,3], L. Le[4]. [1]ARES, NASA Johnson Space Center Houston, TX 77058, USA (michael.e.zolensky@nasa.gov); [2]Dept. Earth and Environmental Sci., Michigan State Univ., East Lansing, MI 48824 USA; [3]Dept. Mineral Sci., National Museum of Natural History, Smithsonian Institution, Washington, DC 20560 USA; [4]Jacobs, Johnson Space Center, TX 77058, USA.

Introduction: C-complex asteroids frequently exhibit reflectance spectra consistent with thermally metamorphosed or shocked carbonaceous chondrites [1], and brecciation [2], including Ryugu [1,3], and Bennu [4]. Petrographic evidence of brecciation has been presented for CM [5], and here we reexamine Cold Bokkeveld, one of the most diverse CM breccias, as a preview of the samples to be returned from Ryugu and Bennu.

Brecciation in Regoliths: The plot in Figure 1 shows Cosmic Ray Exposure (CRE) ages for CMs vs. number of lithologies identified in each meteorite [6, 7, unpublished CRE data from K. Nishiizumi and M. Caffee]. The lithologic heterogeneity vs. exposure-age relationship in Fig. 1 could indicate different responses of homogeneous and heterogeneous meteoroids to the space environment between their onset of exposure (exhumation and ejection from the parent body) and arrival at Earth. The implication of this relation is that samples at the asteroid surface (extrapolating to zero CRE age) will generally consist of very numerous, different lithologies, with varying degree of aqueous alteration, and heating/metamorphism and foreign material. This view is supported by recent imaging and spectroscopic surveys of the regoliths of Ryugu and Bennu performed by the Hayabusa2 and OSIRIS REx spacecraft [1,3,4].

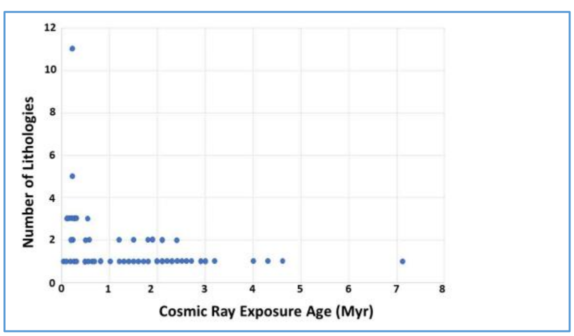

Figure 1. There is an anti-correlation between CRE age and the number of distinct CM lithologies within individual CM chondrites. After [6].

Cold Bokkeveld: In our experience the CMs with the most diverse population of different lithologies include LON 94101 (and litter mates) and Cold Bokkeveld. In this abstract we present results of SEM-EDX and EPMA analyses of two sections of Cold Bokkeveld borrowed from the London Natural History Museum (1727-2 and 1727-3).

Back-scattered electron (BSE) images and quantitative analyses were obtained using the JEOL 7600-FE scanning electron microscope and the JEOL 8530-FE electron microprobe (respectively) at the Astromaterials Research and Exploration Science (ARES) Branch Electron Beam Laboratory, Johnson Space Center. Both examined sections display at least six different CM lithologies, whose differences include size and abundance of chondrules and thickness of chondrule rims, abundance of anhydrous silicates and metal vs fine-grained matrix, and relative abundances of magnetite and Fe-Ni sulfides. These are apparent in Figure 2, where a selection of the CM lithologies is illustrated.

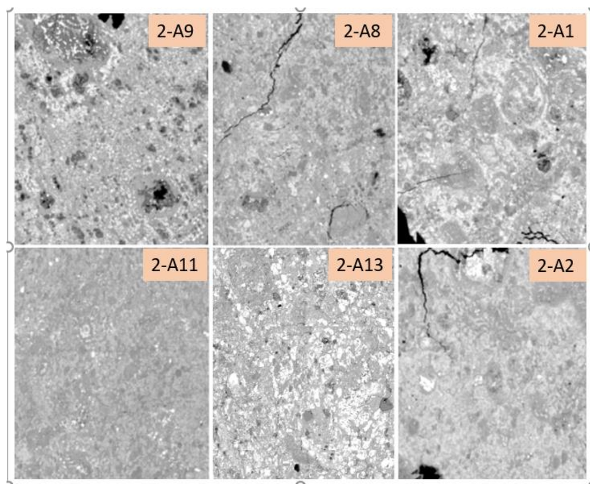

Figure 2: BSE images of six of the different CM lithologies in Cold Bokkeveld section 17-27-2. Each image measures 3 mm across.

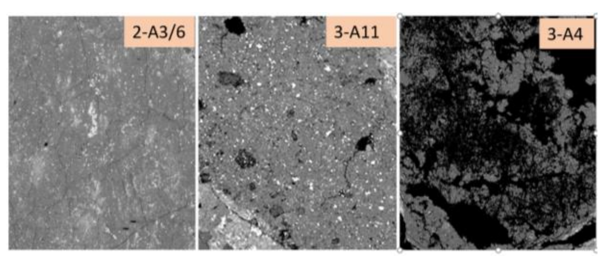

Figure 3: BSE images of three of the unusual type C2 lithologies in Cold Bokkeveld. Views measure 1.5 mm. across. Sadly, lithology 3-A4 has almost been polished away.

In addition to these CM lithologies, these Cold Bokkeveld sections contain several type 2 lithologies that are not obviously CM, and which appear to group into three different materials. These lack chondrules or pseudomorphed chondrules, although some contain a significant quantity of anhydrous silicates, especially forsteritic olivine, so they are not type 1 or obviously CM1. Three of these lithologies are illustrated in Fig. 3.

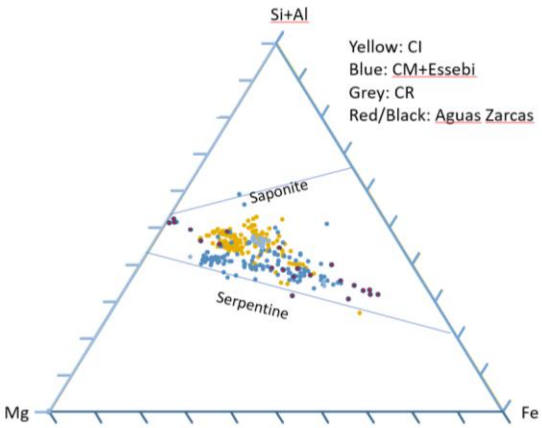

Figure 4: Plot of matrix phyllosilicates in CI (two meteorites), CR (one meteorite), and CM chondrites (six plus Essebi; Aguas Zarcas CM is displayed separately) displayed on a wt. % ternary of Si+Al : Mg : Fe. Lines are provided for "ideal" saponite and chrysotile ("serpentine") compositions.

Phyllosilicate compositions: We have found that one relatively rapid means of discrimination between different C2 carbonaceous chondrites is through EPMA analyses of matrix phyllosilicates, which is not anything new. Figure 4 shows a plot of phyllosilicate compositions for two CI chondrites (Orgueil and Alais), one CR (Renazzo), and six "typical" CM chondrites plus Essebi (plotted together), and Aguas Zarcas CM (displayed separately). In the figure these are displayed in a wt. % ternary of Si+Al : Mg : Fe.

As can be seen in Figure 4, CI and CR phyllosilicates are predominantly a mixture of serpentine type phases (chrysotile and cronstedtite) and saponite. CM compositions, including Aguas Zarcas CM and Essebi (which isn't really a CM) plot nearer the ideal serpentine composition – differences from this are probably due mainly to varying Al composition and Fe charge.

When we add in the phyllosilicates from 21 different Cold Bokkeveld clasts (Figure 5), the plot gets rather complicated, but it is clear is that the entire range of CM phyllosilicates is present in this single CM breccia.

The type 2 lithologies shown in Figure 4 are mineralogically distinct from typical CMs, CRs and CIs in several respects. There are sparse or no large components (chondrules, AOA, CAI), but scattered olivine and low-Ca pyroxene fragments are generally present. Phyllosilicates in lithology 3-A11 are essentially pure saponite, while those in 3-A4 are pure serpentine; the other C2 lithologies contain a mixture of these two phyllosilicates. Lithology 2-A3/6 contains a high concentration of submicron fluorapatite crystals. Magnetite and Fe-Ni sulfides are abundant in some lithologies, but sulfides are rare or absent from 2-A3/6. Fine-grained Ca carbonates and dolomite are present in some lithologies. Andreyivanovite (ideally FeCrP) is present in 3-A3, the second occurrence in nature of this phase (after Kaidun [8]). In summary, these C2 lithologies have experienced incomplete aqueous alteration, but the precursor lithology was probably not CM.

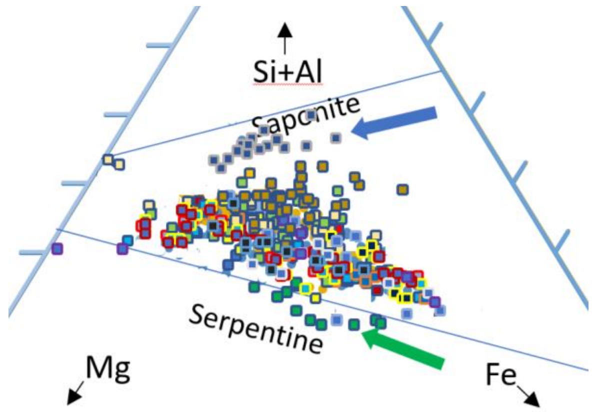

Figure 5: Detail of a plot of matrix phyllosilicates 21 Cold Bokkeveld clasts, displayed on a wt. % ternary of Si+Al : Mg : Fe. Lines are provided for "ideal" saponite and chrysotile ("serpentine") compositions. Note the green symbols (from 3-A4) (see green arrow) lying along the serpentine line, and blue/grey symbols (3-A11) (see blue arrow) lying very close to stoichiometric saponite. These lithologies are shown in Fig. 3.

Implications: If they are anything like brecciated CMs, regolith samples returned from Ryugu and Bennu will be diverse breccias containing materials that experienced varying degrees of aqueous alteration, and probably lithologies not previously available, at present, as separate meteorites.

Acknowledgements: We were supported by the NASA Emerging Worlds and Hayabusa2 Participating Scientist Programs. Samples were provided by the Natural History Museum (London).

References: [1] Moskovitz (2012) *Icarus* in press; [2] Vilas (2008) *Ap. J.* **135**, 1101–1105; [3] Lazaro et al. (2012) *A&A* **549**, L2; [4] Lauretta et al. (2019) *Science* **366**, aay3544 ; [5] Zolensky et al. (2015) *46th LPSC*, abstract; [5] Zolensky and Ivanov (2003) *Chemie de Erde* **63**, 185-246; [6] Zolensky et al. (2014) *45th LPSC*, Abstract 2116; [7] Zolensky et al. (2017) *48th LPSC*, abstract; [8] Zolensky et al. (2008) *Am. Min.* **93**, 1295-1299.