The Relationship Between Cosmic-Ray Exposure Ages And Mixing Of CM Chondrite Lithologies

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Introduction: Carbonaceous (C) chondrites are primitive materials probably deriving from C, P and D asteroids, and as such potentially include samples and analogues of the target asteroids of the Dawn, Hayabusa2 and OSIRIS-Rex missions. Foremost among the C chondrites are the CM chondrites, the most common type, and which have experienced the widest range of early solar system processes including oxidation, hydration, metamorphism, and impact shock deformation, often repeatedly or cyclically [1]. To track the activity of these processes in the early solar system, it is critical to learn how many separate bodies are represented by the CMs.

Nishiizumi and Caffee [2] have reported that the CMs are unique in displaying several distinct peaks for cosmic-ray exposure (CRE) age groups, and that excavation from significant depth and exposure as small entities in space is the best explanation for the observed radionuclide data. There are either 3 or 4 CRE groups for CMs (Fig.1). We decided to systematically characterize the petrography in each of the CRE age groups to determine whether the groups have significant petrographic differences with these reflecting different parent asteroid geological processing or multiple original bodies. We previously reported preliminary results of our work [3], however we have now reexamined these meteorites from the perspective of brecciation, with interesting new results.

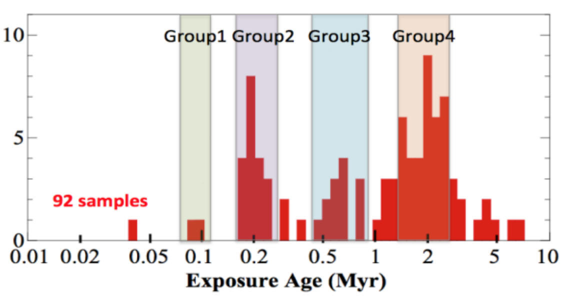

Figure 1. CM CRE ages, showing possible groupings, from [1].

Samples and Methods: As we reported previously [3], we studied thin sections of 110 CM and related chondrites by optical microscopy, scanning electron microscopy (SEM), and electron microprobe microanalysis (EPMA). We attempted to examine every CM that had had a CRE age determined, either by Nishiizumi and Caffee or by previous workers. Seventy four of these are well-determined ages, and 36 are lower limits - >3Myr. CRE ages were measured from all then available CMs, excluding paired samples [2]. We made mosaics of each thin section by reflected light and backscattered electron imaging. Whenever possible we examined multiple thin sections (up to 5) of the meteorites, to include representative sampling (always a problem with small meteorites and even smaller thin sections). We then compared the meteorites, using these criteria:

1. Maximum and minimum sizes of chondrules
2. Shapes of chondrules
3. Degree of chondrule fracturing
4. Maximum thickness of chondrule rims
5. Quantity of anhydrous silicates in chondrules
6. Quantity of metal
7. Quantity of sulfides and tochilinite aggregates
8. CAI abundance

9 Degree of brecciation
and later:
10. Number of distinct lithologies present

These criteria grew from characterizations mentioned in Rubin et al. [1], but evolved and expanded as our study progressed. Our observations were performed qualitatively to compare features with their CRE ages and textures. We used semi quantitative values for each of these criteria generally ranging from 1-5, with 1 being the least. One could improve upon our methodology by using more quantitative measures, but with 110 meteorites and multiple thin sections and mosaics of most to consider this would entail considerable effort.

Results and Discussion: Fig. 1 is the CRE age distribution plot of CMs by [2]. According to this plot, there are several distinct peaks and the large number of samples permits investigation of each CRE age group. However, in this report we largely use the absolute CRE ages rather than inferred groups.

As we reported earlier, we find that some meteorites in the same CRE age indeed have the same lithologies [3]. For example, LON94101, Y-793595 and ALH85007 belong to the same group and some rare clasts (compressed tochilinite) similar to the texture in Y-793595 are found in the other meteorites. This is consistent with the hypothesis that they were ejected by the same collisional event and that each peak in the CRE age distribution plot represents a separate collisional event [2]. However, we also found that CMs with the same CRE ages could have quite different lithologies. In addition, we would see the same distinctive lithologies at different CRE ages.

We then evaluated each meteorite using our criteria, looking for identifiable trends. Although the average chondrule sizes, rim thicknesses, the amount of tochilinite, etc., have no obvious relation to CRE age, the degree of aqueous alteration varies with CRE age, as we previously, tentatively reported [3]. For example, CMs with the youngest CRE ages included all of the meteorites with the lowest amounts of isolated olivine (Fig. 2) and metal (Fig. 3). This suggests that the most altered CMs have younger CRE ages. We are currently analyzing the iron content of matrix serpentine in these particular CMs, because its composition should change with the degree of aqueous alteration.

Since many of these meteorites are polymict breccias (i.e. containing more than one distinctive CM lithology) we decided to reexamine all of our criteria using only meteorites with one lithology. Interestingly, when we did this we found that the comparisons were unchanged. However, we unexpectedly noticed that there is a definite inverse relation between the number of distinctive lithologies within an individual meteorite and its CRE age as shown in Figure 4.

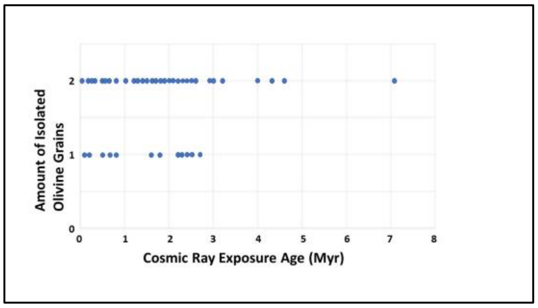

Figure 2. Relative quantity of isolated olivine grains in CMs vs CRE ages. CMs with the least isolated olivine have CRE ages less than 3 Myr.

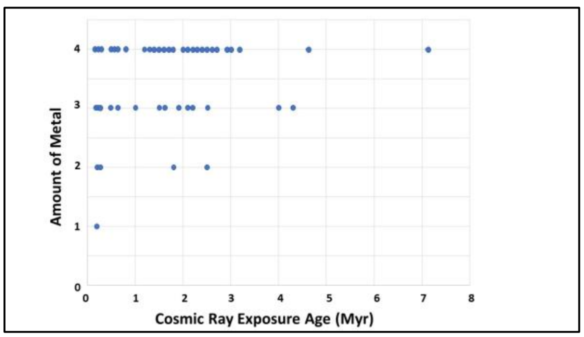

Figure 3. Relative quantity of metal in CMs vs CRE ages. There is a correlation of metal content with CRE age.

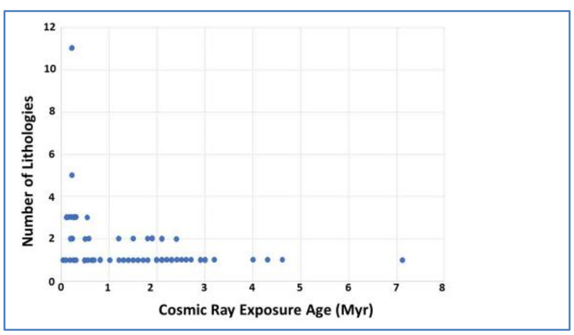

Figure 4. There is an anti-correlation between CRE age and the number of distinct CM lithologies within individual meteorites.

The plot in Figure 4 is only for meteorites with well-measured exposure ages. If we add in the CMs for which there are only lower age limits the trend is the same. *All of the CMs with the longest exposures have a single lithology – though not the same one*. There were originally a few exceptions to this trend, but one by one we found that these meteorites had been misclassified, and were not actually CMs [4].

Conclusions and Speculation: In this study, we sought correlations between the CRE ages and petrography of CMs, and we conclude that the degree of aqueous alteration does appear to vary with the CRE ages – the CMs displaying the most aqueous alteration all have relatively short exposure ages. However, some CM with low degrees of alteration also have short exposures. This relationship is the same regardless of the number of distinctive lithologies a CM possesses. We also found a definite inverse relation between the number of distinctive lithologies in a CM and its exposure age. Since we have examined more than 100 CMs, and up to 5 different thin sections of each meteorite these relationships may indeed be real, and not due to poor statistical sampling.

These relations can be explained in numerous ways. If we, for the moment, limit ourselves to models with a **single CM parent body** one possible explanation is that the degree of aqueous alteration and degree of lithology mixing increases with depth inside of the CM parent asteroid. This picture is consistent with the model proposed by Howard and Bland [5], where there can be circulation of solids in the asteroid's muddy interior. In this model successive impacts would expose successively deeper regions of the CM asteroid, so that the most recently-excavated materials would come from the greatest depths, and potentially have increasing lithologic heterogeneity. Alternatively, the presence of greater lithological heterogeneity at greater depths could be due to changes in the availability of materials during the original accretion of the CM asteroid. Considering **multiple CM parent asteroids**, there may have been two bodies: one homogeneous that broke up earlier, and a heterogeneous second body that broke up later.

Phenomena other than parent-body structure may also explain these observations. The lithologic heterogeneity vs. exposure-age relationship (Fig. 4) 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. Breccias have more internal surfaces of lithologic discontinuity, possibly resulting in weaker meteoroids that disintegrate more readily than their more homogeneous counterparts. However, the abundance of monomict CM breccias at all CRE ages argues against this explanation. The association between high degree of aqueous alteration and younger exposure ages suggests a less-pronounced strength-weakening influence of abundant aqueous alteration products. These and other models can be explored using our observations.

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References: [1] Rubin et al. (2007) *GCA* **71**. 2361-2382. [2] Nishiizumi and Caffee (2012) *LPSC XLIII*, abst #2758. [3] Takenouchi et al. (2013) *Antarct. Meteorites XXXVI*, 69-70. [4] Nakamura et al. (2013) *76th Ann. Meteorit. Soc. Mtg*, #5122. [5] Howard et al. (2011) *GCA* **75**, 2735-2751.