IMPACT-INDUCED AQUEOUS ALTERATION OF CM AND CV CARBONACEOUS CHONDRITES.
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CM chondrites contain ~9 wt.% indigenous water (H_2O+) [1] bound in phyllosilicates; these rocks have experienced variable degrees of parent-body aqueous alteration. The more-altered CM chondrites contain very low modal abundances of metallic Fe-Ni, altered kamacite, high proportions of altered mafic-silicate phenocrysts within chondrules, low amounts of pyrrhotite, diverse carbonate compositions, low modal abundances of PCP clumps (cronstedtite-tochilinite intergrowths, formerly dubbed "poorly characterized phases"), and PCP with low contents of oxidized iron.

In the scheme of Rubin et al. [2] for assessing the degree of CM aqueous alteration, the most-altered CM chondrites (previously classified CM1) are designated CM2.0 (e.g., MET 01070; LAP 02277); the least-altered CM chondrite studied by [2] is CM2.6 QUE 97990. Most CM chondrites are shock-stage S1, but the absence of mafic silicate grains in CM2.0 chondrites precludes their shock-stage classification.

An important question is why some CM chondrites were more aqueously altered than others. Young et al. [3] suggested that down-temperature flow of an aqueous fluid within asteroids was responsible for heterogeneities in the mineralogy and O-isotopic compositions of carbonaceous chondrites. Hydrological activity was modeled as having been caused by the melting of ice, with heat provided by the decay of ^{26}Al [4,5].

Many CM chondrites are regolith breccias containing solar-wind-implanted rare gases [6]. Several CM2.0 chondrites have a prominent foliation wherein chondrules and other components are approximately aligned [2,7,8]. Similar foliations in ordinary and carbonaceous chondrites were ascribed to impact-induced collapse of matrix pores and the squeezing of chondrules into pore spaces [9,10]. This is consistent with shock recovery experiments on CM2.5 Murchison and CV3 Allende that produced whole-rock foliations and caused flattening of spheroidal chondrules [10,11].

The significant number of CM breccias and the prominent impact-induced petrofabrics in CM2.0 samples raise the possibility that collisions might be responsible for the aqueous alteration of CM chondrites.

CV chondrites also have members with prominent petrofabrics [9,12-15]. This group has been divided into three subgroups: (1) a reduced subgroup ($CV3_R$) characterized by high metal/magnetite modal ratios, low-Ni metal and low-Ni sulfide; (2) an Allende-like oxidized subgroup ($CV3_{OxA}$) characterized mainly by having had some chondrule primary minerals replaced by magnetite, Ni-rich sulfide, ferroan olivine and feldspathoids; and (3) a Bali-like oxidized subgroup ($CV3_{OxB}$) characterized by abundant phyllosilicates and chondrules with many primary minerals having been replaced by phyllosilicate, magnetite, Ni-rich sulfide, very ferroan olivine, and hedenbergite [16-18]. The $CV3_{OxB}$ subgroup is the most altered; it contains more matrix material, less metal, more-ferroan olivine, and more phyllosilicates than $CV3_{OxA}$ rocks.

I studied CV3 MCY 05219 (S3) and found it to contain abundant magnetite and Ni-bearing sulfide, accessory hedenbergite, and very little metallic Fe-Ni. It is probably a member of the CV_{OxB} subgroup.

Using the measure tool of Adobe Photoshop on digital images of BSE mosaics of CM thin sections and on a transmitted-light photograph of MCY 05219, I computed the azimuth of the long axis of each chondrule, CAI, AOI and PCP clump ≥250 μm in size. The percentage of particles with long axes within 10º of the median azimuth in each CM chondrite tends to decrease with increasing petrologic subtype: i.e., the less-altered rocks tend to have fewer aligned particles. Particle alignment and CM subtype is strongly anticorrelated ($r = -0.92$, $n = 9$, $2\alpha = 0.00014$), significant at the 99.96% confidence level. It is clear that, with increasing degrees of aqueous alteration, CM chondrites exhibit more-pronounced petrofabrics. MCY 05219 also has a strong petrofabric, similar to that of MET 01070.

CV3 chondrites with pronounced petrofabrics include $CV3_R$ rocks and members of $CV3_{OxB}$ [9,12,15]. Because the shock stages of those CV chondrites studied by [9] that do not have a petrofabric are nearly all S1, it is clear that there is a correlation between shock stage and petrofabric strength among CV chondrites.

Strictly elastic waves resulting from subsonic impacts cannot be responsible for the development of CM petrofabrics because such waves do not result in permanent deformation of the target [19]. Instead, hypervelocity impact events are probably responsible, but the unshocked nature of CM olivine grains implies that the shock wave had largely dissipated before it could deform the olivine crystals. This is possible because CM chondrites are porous rocks with ~60 vol.% matrix; in porous bodies shock waves attenuate rapidly away from the impact site. It seems plausible that the attenuated shock waves could still cause the collapse of matrix pores and the squeezing of chondrules into pore spaces in matrix-rich samples without causing most olivine grains to develop undulose extinction.

The situation is different for CV chondrites: nearly every CV3 with a petrofabric is S3 or S4; nearly every CV3 without a petrofabric is S1. I suggest that the lower modal abundance of matrix in CV3 chondrites (~35 vol.%) compared to CM chondrites (~60 vol.%) attenuates shock waves less effectively, allowing more material near the crater to experience high shock pressures and for mafic silicates to exhibit shock effects.

Many olivine grains in CM2.2 Nogoya are transected by irregular fractures on the sides of which the olivine has been aqueously altered. The fractures in the olivine grains formed before the rock was altered, indicating that some impact events preceded aqueous alteration on the CM asteroid. However, it cannot be established if the impact events that caused the olivine grains in Nogoya to fracture are the same ones responsible for producing the petrofabrics in CM chondrites.

I assume that small-scale hypervelocity collisions occurred randomly on the CM asteroid. Although the shock waves attenuated rapidly away from the impact site, they caused some CM regions to become more deformed and fractured than others. The more-deformed regions developed stronger petrofabrics, more extensive fractures, and greater porosity than regions that experienced less impact-induced shear.

Water was eventually mobilized on the CM asteroid, perhaps by subsequent impact-induced dehydration of phyllosilicates or by the impact melting of ice. The water seeped into essentially all CM chondrites, but more water was retained in rocks with more fractures and greater porosity, i.e., those CM chondrites that had been more significantly affected by impacts and exhibited stronger petrofabrics. These are the same rocks that became more aqueously altered. This can account for the strong anticorrelation in CM chondrites between petrologic subtype and particle alignment.

The situation is somewhat different for CV chondrites. Among the CV chondrites with petrofabrics, half are $CV3_R$ and half are $CV3_{OxB}$; none is a member of the less-altered $CV3_{OxA}$ subgroup. I suggest that the reduced CV chondrites formed from material that had previously been compacted by impacts. The porosities of $CV3_R$ samples are 0.6 – 8% [20]. Hypervelocity impacts into this compacted material shocked many of these rocks to S3-S4 levels and produced petrofabrics within them as pores collapsed and chondrules were squeezed into pore spaces. The $CV3_R$ chondrites remained relatively unaltered and unoxidized even after water was subsequently mobilized by impact heating of phyllosilicates or ice; this is because the low porosities of these rocks permitted relatively little water to seep into them to facilitate alteration.

In contrast, the members of the two oxidized CV subgroups formed from more-porous, less-compacted materials (their porosities are typically 20-28% [20]). Some of the more-porous CV chondrites (the $CV3_{OxB}$ samples) were significantly shocked, typically reaching shock-stage S3. They were heavily fractured and developed strong petrofabrics. When water was subsequently mobilized, they became greatly altered because there were many sites where water could be retained. Abundant phyllosilicates formed in the matrix and most metal grains were replaced by magnetite.

The $CV3_{OxA}$ samples formed from similar porous, uncompacted materials but remained essentially unshocked (shock-stage S1). They were not extensively fractured and did not develop noticeable petrofabrics. Nevertheless, because of their high initial porosity, the $CV3_{OxA}$ samples became significantly altered when water was later mobilized. Because the $CV3_{OxA}$ samples were not as fractured (by shock) as the $CV3_{OxB}$ samples, their overall degree of alteration was somewhat less. Phyllosilicates formed much less abundantly in the $CV3_{OxA}$ matrix regions and less metallic Fe-Ni was converted into magnetite.

The oxidized CV subgroups may have been able to retain some of their initial nebular porosity because they experienced less parent-body impact-compaction than other, lower-porosity, CV3 chondrites.

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