PROGRESSIVE ALTERATION OF CM CHONDRITES: EFFECTS ON REFRACTORY INCLUSIONS.

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Introduction

CM chondrites are aqueously altered rocks that contain ~9 wt.% H_2O^+ (indigenous water) [1] bound in phyllosilicates [2-4]; also present in the matrix are serpentine-tochilinite intergrowths (PCP), pentlandite, and Ni-bearing pyrrhotite. The extent of alteration varies from meteorite to meteorite. Some CM chondrites contain well-delineated metallic-Fe-Ni-bearing, olivine- and pyroxene-rich chondrules; others are rich in phyllosilicates and sulfide and contain chondrule pseudomorphs with no olivine or pyroxene and very little metallic Fe-Ni. There is a broad consensus that CM-chondrite alteration took place on the parent asteroid [2,4,5-10].

Whole-rock Aqueous Alteration

McSween [5] used the modal contents and Fe/Si ratios of fine-grained matrix material to construct an alteration sequence for CM chondrites. He placed individual chondrites into three categories: partially altered (e.g., Murchison; Murray), altered (e.g., Cold Bokkeveld) and highly altered (Nogoya). Browning et al. [11] and Hanowski and Brearley [12] identified several mineralogical and textural properties that reflect progressive CM alteration; these include changes in hydrated mineral compositions, destruction of isolated silicate grains in the fine-grained matrix, and alteration of mafic silicates within chondrules. Browning et al. [11] devised a "mineralogic alteration index" that ranked CM chondrites by their degree of alteration.

Rubin et al. [13] studied 11 CM chondrites that span the range from least altered to most altered. They used various petrologic properties (many previously identified) that provide information regarding the degree of aqueous alteration. Some properties result from processes associated with early and intermediate stages of the alteration sequence (i.e., hydration of matrix, alteration of primary igneous glass in chondrules and production of large PCP clumps). Other petrologic properties reflect processes active throughout the alteration sequence; these include oxidation of metallic Fe-Ni, alteration of chondrule mafic phenocrysts, changes in PCP composition (reflecting an increase in the phyllosilicate/sulfide ratio), and changes in carbonate mineralogy (reflecting the development of dolomite and complex carbonates at the expense of Ca carbonate).

Based on these parameters, Rubin et al. [13] proposed a new aqueous alteration index for CM chondrites. Because there are no CM samples that display only incipient alteration, the least altered sample was arbitrarily assigned to subtype 2.6. The most altered CM chondrites, currently classified CM1, were assigned to subtype 2.0. These rocks have essentially no mafic silicates; they contain chondrule pseudomorphs composed mainly of phyllosilicate. They are closer in texture to other CM2 chondrites such as QUE 93005 than to CI1 chondrites.

Rubin et al. [13] assigned petrologic subtypes (±0.1) to every CM chondrite in their study: QUE 97990, CM2.6; Murchison, CM2.5; Kivesvaara, CM2.5; Murray, CM2.4/2.5; Y-791198, CM2.4; QUE 99355, CM2.3; Nogoya, CM2.2; Cold Bokkeveld, CM2.2; QUE 93005, CM2.1; LAP 02277, CM2.0; MET 01070, CM2.0.

Refractory Inclusions

Refractory inclusions vary in mineralogy and modal abundance in carbonaceous chondrites that have experienced different degrees of aqueous alteration.

Proportions of Melilite-bearing Inclusions. The most primitive carbonaceous chondrites contain abundant melilite-rich refractory inclusions. About 45% of all refractory inclusions in type-3.0 CO chondrites are melilite-rich [14].

Acfer 094 is a CM-related, type-3.0 carbonaceous chondrite that has experienced negligible thermal metamorphism. The most abundant phases in refractory inclusions in Acfer 094 are melilite and spinel [15].

Approximately half of the refractory inclusions in CR2 chondrites are melilite-rich [16,17]. Although these rocks have undergone aqueous alteration, most alteration effects are confined to the fine-grained serpentine- and saponite-rich matrix [18]. CR chondrites possess abundant metallic Fe-Ni; several rocks contain chondrules with unaltered (or only slightly altered) glassy mesostases [16].

In those CO3 chondrites that have experienced intermediate degrees of aqueous alteration (e.g., CO3.4 Lancé), melilite is replaced by nepheline, feldspathoids, diopside and sulfide [14]. In the most altered CO3 chondrites (type 3.5 – 3.7), no inclusions are melilite rich [14].

This trend is also evident among refractory inclusions in CV3 chondrites. Oxidized CV meteorites such as Allende (which have experienced appreciable whole-rock aqueous alteration [19]) contain fluffy type-A inclusions wherein most of the primary melilite has been replaced by fine-grained secondary alteration products (anorthite, nepheline, grossular and sodalite) [20]. Reduced CV meteorites such as Vigarano (which have experienced much less whole-rock alteration) contain essentially unaltered melilite [21].

Melilite is very rare in aqueously altered CM chondrites. Nevertheless, MacPherson et al. [22] reported a few fragments of melilite-rich inclusions in CM2.5 Murchison; the inclusions were derived from freeze-thaw disaggregation of the meteorite and heavy-liquid separations. MacPherson et al. [22] suggested that the fragments may have been derived from a single disrupted melilite-rich inclusion. However, most refractory inclusions in Murchison consist mainly of hibonite, olivine-pyroxene, and spinel-pyroxene [23,24].

More-altered CM chondrites completely lack melilite-rich inclusions. Mighei contains hibonite-, spinel- and pyroxene-rich inclusions [25]. The mineralogical alteration index of Browning et al. [11] places Mighei about halfway between Nogoya and Murray (classified here as type 2.2 and 2.4/2.5, respectively). Hence, Mighei is probably type ~2.3.

None of the 345 refractory inclusions and inclusion fragments in CM2.2 Cold Bokkeveld contains melilite [26]. In order of decreasing abundance the inclusions are spinel-pyroxene (48%), spinel (46%), spinel-pyroxene-olivine (4%), spinel-olivine (2%) and hibonite (0.3%).

I identified 40 refractory inclusions in a single thin section (,13) of CM2.6 QUE 97990, the least-altered CM2 chondrite known. Inclusion varieties include simple, banded and nodular structures as well as simple and complex aggregates. The inclusions range in mean size from 30 to 530 µm and average 130±90 µm. Most inclusions contain FeO-rich phyllosilicate; several contain small grains of perovskite. The most abundant inclusions consist mainly of spinel-pyroxene (35%), followed by spinel (20%), spinel-pyroxene-olivine (18%), pyroxene (12%), pyroxene-olivine (8%) and hibonite (8%). Four pyroxene phases occur: diopside, Al-rich diopside, fassaite and (in two inclusions) enstatite. No inclusions contain melilite. Although 65% of the inclusions are largely intact, all of the spinel inclusions are fragments.

Because melilite is extremely rare to absent in refractory inclusions in CM chondrites of type ≤2.6, the presence of a significant number of melilite-rich inclusions in a CM chondrite would indicate that it is subtype 2.7 – 3.0.

Modal Abundance and Number Density of Refractory Inclusions. In addition to causing the replacement of melilite by secondary products [14], whole-rock aqueous alteration of carbonaceous chondrites causes refractory inclusions to fragment and disintegrate.

For example, fine-grained refractory inclusions in CO3 chondrites may have formed by the breakdown of melilite-rich inclusions during aqueous alteration [14]. If the fine-grained inclusions are excluded from consideration, the number density of the remaining refractory inclusions tends to decrease with increasing degrees of whole-rock alteration: CO3.0 ALH A77307 contains 0.28 inclusions/mm^2; CO3.4 Lancé contains 0.24 inclusions/mm^2; CO3.6 Warrenton and CO3.7 Isna each contain 0.16 inclusions/mm^2.

Disintegration of refractory inclusions also occurred in CM chondrites.

CM2.6 QUE 97990 contains 1.8 vol.% refractory inclusions; 40 occur within an area of ~0.5 cm^2, equivalent to a number density of ~80 inclusions/cm^2.

My observations of x-ray maps made at UCLA of two 1-mm^2 portions of a thin section of CM2.4 Y-791198 revealed one 83×174-µm-size, spinel-rich refractory-inclusion fragment. With high uncertainty, this is equivalent to a modal abundance of ~0.7 vol.% and a number density of ~50 inclusions/cm^2.

Mighei (estimated to be type 2.3) contains ~10 inclusions/cm^2 [25]. From the published values of the inclusion sizes and thin section area, I calculate that the modal abundance of refractory inclusions in Mighei is ~0.6 vol.%.

Cold Bokkeveld (CM2.2) contains ~60 refractory inclusions/cm^2 [26], but almost all are fragments of larger disrupted objects. The abundance of largely intact refractory inclusions in Cold Bokkeveld is probably on the order of 5 inclusions/cm^2, with a modal abundance of ~0.001 vol.%.

There thus appear to be trends for the modal abundance and the number density of largely intact refractory inclusions to decrease with increasing degrees of aqueous alteration [27]. These trends could potentially serve as an additional classification parameter for CM alteration.

Origin of Spinel Inclusions. Equilibrium thermodynamic calculations show that spinel condenses at lower temperatures than melilite from a gas of solar composition. Several workers have developed complex models to account for the occurrence of melilite-free spinel inclusions in CM chondrites; these include formation by a process involving loss of melt from partially molten inclusions that contained solid grains consisting solely of spinel [28,29] and "some kind of nebular condensation combined with aggregation [25]."

It seems more likely that melilite-free spinel inclusions in CM chondrites formed by aqueous alteration and disaggregation of melilite-bearing inclusions. The process involved alteration of primary melilite, enhancing inclusion friability. Subsequent fragmentation of the inclusions dislodged other phases (e.g., olivine, pyroxene, hibonite) and separated them from spinel. This is consistent with the fragmental nature of all of the spinel inclusions in QUE 97990.

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