PCA 02012: A UNIQUE THERMALLY METAMORPHOSED CARBONACEOUS CHONDRITE.

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Introduction: Based on the evidence derived from spectroscopic observation and meteorite analysis, it has been proposed that some C type asteroids were heated and dehydrated after aqueous alteration [e. g., 1]. Constraints on metamorphic processes that affected these C type asteroids may come from the study of a significant number of thermally metamorphosed carbonaceous chondrites (TMCCs) that have been found in Antarctica [e. g., 2, 3] and in hot desert environments [4]. Studies of TMCCs indicate that the conditions of thermal metamorphism experienced by these meteorites may have been quite variable, suggesting that metamorphism of the TMCCs was complex [e.g., 5, 6].

Recently, we have identified the Antarctic find, PCA02012 as a new member of the TMCC group. Here we report preliminary results on the petrology, mineralogy, chemical composition, oxygen isotopic composition, maturity of organics, and reflectance spectra of this meteorite and use these data to constrain the degree of heating of PCA02012.

Experimental procedures: To identify samples that have experienced thermal metamorphism, we focused on fine-grained phyllosilicate-rich matrix because it can be a sensitive indicator of heating. The detailed mineralogy was determined by synchrotron X-ray diffraction (S-XRD) analysis on small pieces (~200 µm) of matrix of PCA 02012. Further, the microstructural and microchemical characteristics of the matrix were determined using transmission electron microscopy (TEM), FE-SEM/EDS, and electron microprobe analysis. The maturity of organics in the matrix was determined by micro-Raman spectroscopy. In addition, the oxygen isotopic compositions of the bulk chondrite was analyzed by laser fluorination oxygen isotope mass spectrometry using a CO_2 laser and BrF_5 fluorination system [7]. The visible and near-infrared (VNIR) (0.3-2.5 µm) and FT-IR (1.7-25 µm) reflectance spectra of PCA 02012 were measured. During the FT-IR measurement the sample was heated to ~100 ºC to remove any effects of adsorbed water on the surface of sample.

Results: PCA 02012 is classified as a CM2 based on preliminary observations reported in [8]. The meteorite mainly consists of fine-grained matrix with larger and coarser grained components such as chondrules and CAIs embedded within the matrix. FEGSEM observations show that there is no evidence of significant Fe-Mg diffusion into forsteritic chondrule olivines that would be expected in samples which experienced long duration thermal metamorphism, such as that observed in CO and UOC meteorites. Instead, based on FE-SEM/EDS analysis, a very narrow zone of Fe-enrichment ~3 µm in width is apparent at the periphery of forsteritic olivine in type IA chondrules.

TEM and STEM studies confirm that the mineralogy of PCA 02012 matrix clearly differs from that of typical CM2 matrix. Figure 1 is a bright field TEM image of a region of matrix in PCA 02012 prepared by the FIB technique. The matrix mainly consists of fine-grained FeO-rich olivine and low-Ca pyroxene with grain sizes of ~ 0.1 µm, and shows a granoblastic texture with common triple junctions. The chemical composition of olivine determined by analytical electron microscopy exhibits a narrow range (Fa_{51-65}). Interestingly, albite is also a relatively common phase in the matrix. Fe sulfide, chromite, and Fe-Ni metal occur as minor phases. Phyllosilicates that are the dominant phase in most CM2 matrices are completely absent.

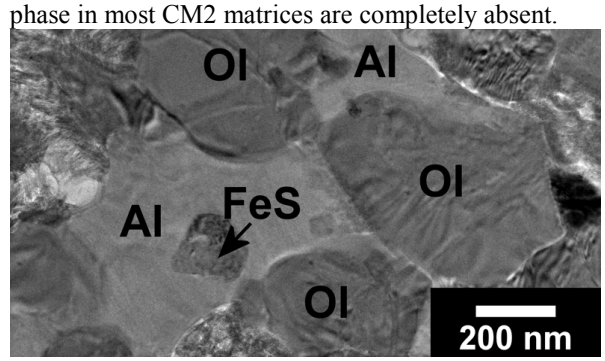

Figure 1. Bright field TEM image of matrix in PCA 02012. The matrix consists of FeO-rich olivine and low Ca-pyroxene with albite and exhibits a granoblastic texture. Ol: olivine, Al: albite, FeS: Fe-sulfide.

The matrix in PCA 02012 shows the highest maturation grade of organics found so far in any TMCC studied. PCA 02012 has a higher organic maturity than samples of Murchison heated at 900 ºC [9]. In the high temperature region, the maturation grade seems to be unchanged by heating duration, but is highly dependant on the heating temperature. We estimate the heating temperature of PCA 02012 to be higher than 900 ºC.

The chemical composition for matrix in PCA 02012 was obtained by EPMA using a 20 µm broad beam. The analytical totals provide further evidence that the matrix was dehydrated. PCA 02012 matrix analyses have high analytical totals (~95%) compared to typical

CM2 matrices which contain abundant hydrous phyllosilicates (~80% reported in [9]). However, the elemental composition of PCA 02012 matrix is similar to that of typical CM2 chondrites indicating that the precursor of PCA 02012 before thermal metamorphism was probably a CM2 chondrite. In addition, tochilinite/cronstedtite aggregates, which are common in CM2s are absent in PCA 02012. Instead, porous sulfide-metal aggregates are present. All of these features are similar to those found in Belgica (B-) 7904 and Dhofar (Dho) 735, both of which are known as strongly heated CCs from previous studies [2, 4].

The oxygen isotope compositions of PCA 02012 plot on a line with a slope of a 1/2 that is an extension of the typical CM2 compositional field. The $\delta^{18}O$ values are approximately 5 ‰ higher than that of typical CMs. These results can be explained by a mass dependent fractionation caused by heating and dehydration resulting in a heavy isotope enrichment. This interpretation is consistent with the oxygen isotope ratios of experimentally heated Murchison reported in [4]. Murchison samples heated at 930 °C for 1 hour have a $\delta^{18}O$ value 4.5 ‰ higher than unheated Murchison.

The reflectance spectra of PCA 02012 is clearly different from typical CM2s. The 0.7 µm absorption, which is derived from Fe^{2+}–Fe^{3+} charge transfer in phyllosilicates, is never observed in PCA 02012. Based on heating experiments of Murchison [10], this absorption band disappears at 400 °C after 1 week.

Discussion: Although PCA 02012 has the typical textural characteristics of a CM2, its mineralogical characteristics, maturity of organics, and oxygen isotopic ratios are distinct from typical CM2s. These observations demonstrate that PCA 02012 is a TMCC. Assuming the meteorite was a typical CM2 before heating, the absence of phyllosilicates in the matrix shows that complete dehydration has occurred resulting in the formation of fine-grained FeO-rich olivines and pyroxenes. In this thermal event, tochilinite/cronstedtite aggregates also decomposed to form the sulfide-metal aggregates that are present in the matrix.

Unlike the thermal metamorphism that is typical of other chondrite groups, like CO and ordinary chondrites, the heating event which affected PCA 02012 appears to have been short-lived. The following lines of evidence indicate that this heating event could not have continued for more than several 10s at temperatures at least 900 ºC suggested by maturity of organics. First, evidence of Fe-Mg interdiffusion between chondrule olivine and matrix is minimal. Based on a calculation using the Fe-Mg diffusion coefficients of [11], the estimated duration of heating at 900 ºC is 100 hours. Second, the estimated temperature of PCA 02012 from thermal maturation of organics, based on experimental data, is over 900 ºC. Third, the very fine-grained granoblastic texture of the matrix requires short duration heating to prevent Ostwald ripening of olivines. The granoblastic texture in PCA 02012 is similar to amoeboid olivine aggregates (AOAs) in C2 - C3 chondrites, but is much finer grained (100 nm c.f. microns to 10s of microns in AOAs). Annealed textures similar to those in AOAs have been reproduced by heating experiments on anorthite and San Carlos olivine at various temperature for 3 - 100 h [12]. The texture consisting of silicate grains ~10 µm in size formed after 3 h at 1288 °C. This experiment provides qualitative confirmation that a) the textures in PCA 02012 were produced by annealing, and 2) annealing temperatures were much lower than 1288 °C, as indicated by very small grain size of PCA 02012. We cannot constrain the heating duration for PCA 02012 from these experiment; further annealing studies are needed to address this issue. Neverthless, taking all these observations together, we suggest that it is possible to reproduce both the fine-scale granoblastic matrix texture of PCA 02012 and reproduce the heavy oxygen isotope composition of the bulk chondrite by a short duration heating event at temperatures of ~ 900°C.

The oxygen isotope compositions of the most strongly TMCCs ever discovered (e.g. B-7904) are completely different from those of typical CMs. They have smaller $\Delta^{17}O$ values, even if they have textural and petrologic characteristics that are similar to those of CMs. Thus, PCA 02012 represents the first example of a thermally metamorphosed CM chondrite that has been identified based on its mineralogy and oxygen isotope ratio. This observation indicates a new diversity of heating process of CM chondrite and new insights into the thermal history of C type asteroids.

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