



# Why is it so difficult to classify Renazzo-type (CR) carbonaceous chondrites? – Implications from TEM observations of matrices for the sequences of aqueous alteration

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## Abstract

A number of different classifications have been proposed for the CR chondrites; this study aims at reconciling these different schemes. Mineralogy-based classification has proved particularly challenging for weakly to moderately altered CRs because incipient mineral replacement and elemental mobilization arising from aqueous alteration only affected the most susceptible primary phases, which are generally located in the matrix. Secondary matrix phases are extremely fine-grained (generally sub-micron) and heterogeneously mixed with primary nebular materials. Compositional and isotopic classification parameters are fraught with confounding factors, such as terrestrial weathering, impact processes, and variable abundance of clasts from different regions of the CR parent body or from altogether different planetary bodies. Here, detailed TEM observations from eighteen FIB sections retrieved from the matrices of nine Antarctic CR chondrites (EET 96259, GRA 95229, GRO 95577, GRO 03116, LAP 02342, LAP 04516, LAP 04720, MIL 07525, and MIL 090001) are presented, representing a range of petrologic types. Amorphous Fe–Mg silicates are found to be the dominant phase in all but the most altered CR chondrite matrices, which still retain significant amounts of these amorphous materials. Amorphous Fe–Mg silicates are mixed with phyllosilicates at the nanometer scale. The ratio of amorphous Fe–Mg silicates to phyllosilicates decreases as: (1) the size of phyllosilicates, (2) abundance of magnetite, and (3) replacement of Fe–Ni sulfides increase. Carbonates are only abundant in the most altered CR chondrite, GRO 95577. Nanophase Fe–Ni metal and tochilinite are present small abundances in most CR matrices. Based on the presence, abundance and size of phyllosilicates with respect to amorphous Fe–Mg silicates, the sub-micron features of CR chondrites have been linked to existing classification sequences, and possible reasons for inconsistencies among classification schemes are discussed.

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## 1. INTRODUCTION

Often used as representative of the most pristine of solar system materials, carbonaceous chondrites bear signs of one of the earliest planetary processes – alteration by liquid

water. One of the main mechanisms for incorporating water into chondrites is via aqueous alteration in asteroid parent bodies. Thus the carbonaceous chondrites represent the ground truth for two of the biggest questions in planetary science: (1) what were the starting materials from which the solar system formed and (2) how did water and other volatiles interact with these starting materials. Water in chondrites is bound in crystalline and amorphous materials (e.g., [Garenne et al., 2014](#); [Le Guillou et al., 2015](#)) and in

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rare cases observed in fluid inclusions (e.g., Zolensky et al., 1999, 2004; Zolensky et al., 2000)

Aqueous alteration of carbonaceous chondrites has produced a diverse suite of secondary products (e.g., Brearley and McSween, 2006; Huss et al., 2006; Zolensky et al., 2008; Brearley, 2014). Complex asteroidal alteration hypotheses have emerged from attempting to explain the formation of these alteration phases. In CI and CM chondrites, alteration was so pervasive that multiple reactions overprinted each other. With many reactions having run to completion, we are left with a recognition that aqueous alteration was key process in the early history of asteroids, but also with few constraints as to the conditions and the reactant phases present, in particular in the most altered chondrites. One group of carbonaceous chondrites provides a “welcome path” toward answers: the CRs. CRs have the same basic mineralogy and chemical composition as other aqueously altered chondrites (Table 1), but some of them exhibit only very minor conversion of nebular materials into secondary minerals compared with most meteorites from other groups (Abreu and Brearley, 2010). As a result, the CRs are simultaneously one of the best places to look for virtually unaltered solar nebula material and to observe aqueous alteration in progress, with both the reactants and products remaining observable and in physical contact.

Members of the CR group show the full range of aqueous alteration and have affinities with other groups of hydrous meteorites. Similarities between the alteration styles of CR2s and CIs have been previously noted (Bischoff et al., 1993; Zolensky et al., 1993; Kallemeyn et al., 1994). Alteration of CIs resulted in the formation of phyllosilicates, oxides, carbonates, sulfides, and sulfates (Kerridge et al., 1979; Tomeoka et al., 1988; Zolensky et al., 1993). CRs, CIs and some CMs share the presence of framboidal and platelet magnetite. The mineralogy of some CR matrices also resemble assemblages in CM chondrite matrices (Abreu and Stanek, 2012). Alteration of CM matrices resulted in the formation of phyllosilicates, tochilinite, carbonates, sulfides, sulfates, oxides, and hydroxides (e.g., McSween, 1979; Tomeoka and Buseck, 1985; Zolensky et al., 1993; Browning et al., 1996; Hanowski and Brearley, 2001; Zega and Buseck, 2003; Rubin et al., 2007; Chizmadia and Brearley, 2008; de

Leuw et al., 2010; Hewins et al., 2014). Abreu (2007) observed that in some CRs increasing degree of aqueous alteration is associated with declining Mg/Fe ratios in the matrix, owing to the formation of larger (>1micron) Fe-oxides and Fe-sulfides. This observation is in agreement with features attributed to alteration of CMs (e.g., McSween, 1979).

Although CR chondrites share many similarities with CI and CM chondrites, the matrices of these meteorites contain variable amounts of amorphous Fe–Mg silicates (e.g. Abreu and Brearley, 2010; Le Guillou et al., 2015). Le Guillou et al. (2015) used a combination of STXM and TEM data to determine the Fe-oxidation state of CR matrix silicates. Le Guillou et al. (2015) studied three of the same samples as the present study (GRA 95229, LAP 02342, and GRO 95577) and two different members of the EET 87XXX-pairing group (EET 8770 and EET 92042) to which EET 92062 belongs. They suggested that aqueous alteration of amorphous silicates is a two-step process that begins with hydration of amorphous silicates followed by phyllosilicate formation. Le Guillou et al. (2015) argued that both processes ought to have occurred in an asteroidal environment.

The abundance and origin of alteration products are codified in the petrologic sequence, in which chondrites that have not been affected by asteroidal processes are assigned type 3. Increasing effects of aqueous alteration in replacing solar nebula mineral assemblages are denoted by petrologic types 1–2. Three scales have been devised to quantify the degree of aqueous alteration of CRs. Alexander et al. (2013) observed that there was a linear relationship between bulk H, C and N elemental and isotopic composition of CMs and CRs and used this correlation to assign petrologic subgroups. Harju et al. (2014) postulated petrologic criteria to classify the CRs: (1) presence/abundance of chondrules containing altered mesostasis, (2) presence/abundance of magnetite, (3) replacement of primary silicate phenocrysts by phyllosilicates, (4) replacement of Fe–Ni metal with oxides, (5) abundance of phyllosilicates in matrix and chondrule rims, and (6) S-content of the matrix. Rubin et al. (2007) proposed a similar set of criteria to classify CM chondrites according to their degree of aqueous alteration. Finally, Howard et al. (2015a) used the ratio of phyllosili-

Table 1  
Petrographic and mineralogical characteristics of chondrules, metal, and matrix in CR chondrites.

Components	Distinguishing features	Aqueous alt. products
Chondrules [1–8], ~65 vol.% – [1]	Large (<1 mm), most are MgO-rich type I, some type II	Only CR1 show replacement of silicate phenocrysts [e.g., 11]. Mesostasis is replaced by serpentine and chlorite
Fe–Ni metal (~9 vol.% – [1])	Abundant Fe–Ni metal, mainly kamacite, containing 4–8 wt.% Ni. Near solar Ni/Co ratios [12–15]	Oxides, hydroxides
Matrix [2,3–11] (~35 vol.% – [1])	Dominance of amorphous Fe-rich silicates in matrices [10]	Matrix phases are progressively replaced by phyllosilicates: Fe-rich serpentine and saponite [1–11] and less abundant cronstedtite. Calcite. Framboidal magnetite [e.g. 6]. Hydrated sulfides (i.e., tochilinite – [16])

[1] Schrader et al. (2011); [2] Weisberg et al. (2006); [3] Weisberg et al. (1993) [4] Zolensky et al. (1993); [5] Weisberg et al. (1995); [6] Kallemeyn et al. (1994); [7] Krot et al. (2002); [8] Brearley and McSween (2006); [9] Abreu (2007); [10] Abreu and Brearley (2010); [11] Harju et al. (2014); [12] Lee et al. (1992); [13] Connolly et al. (2001); [14] Ebel et al. (2008); [15] Wasson and Rubin (2010); [16] Abreu and Stanek (2012).

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