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Spectral reflectance properties of carbonaceous chondrites: 3. CR chondrites

E.A. Cloutis [a],*, P. Hudon [b,1], T. Hiroi [c], M.J. Gaffey [d]

[a] Department of Geography, University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba, Canada R3B 2E9
[b] Astromaterials Research and Exploration Science Office, NASA Johnson Space Center, Mail Code KR, 2101 NASA Road 1, Houston, TX 77058-3696, USA
[c] Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912-1846, USA
[d] Department of Space Studies, University of North Dakota, PO Box 9008, Grand Forks, ND 58202-9008, USA

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ABSTRACT

Powdered samples of a suite of 14 CR and CR-like chondrites, ranging from petrologic grade 1 to 3, were spectrally characterized over the 0.3–2.5 μm interval as part of a larger study of carbonaceous chondrite reflectance spectra. Spectral analysis was complicated by absorption bands due to Fe oxyhydroxides near 0.9 μm, resulting from terrestrial weathering. This absorption feature masks expected absorption bands due to constituent silicates in this region. In spite of this interference, most of the CR spectra exhibit absorption bands attributable to silicates, in particular an absorption feature due to Fe^{2+}-bearing phyllosilicates near 1.1 μm. Mafic silicate absorption bands are weak to nonexistent due to a number of factors, including low Fe content, low degree of silicate crystallinity in some cases, and presence of fine-grained, finely dispersed opaques. With increasing aqueous alteration, phyllosilicate: mafic silicate ratios increase, resulting in more resolvable phyllosilicate absorption bands in the 1.1 μm region. In the most phyllosilicate-rich CR chondrite, GRO 95577 (CR1), an additional possible phyllosilicate absorption band is seen at 2.38 μm. In contrast to CM spectra, CR spectra generally do not exhibit an absorption band in the 0.65–0.7 μm region, which is attributable to Fe^{3+}–Fe^{2+} charge transfers, suggesting that CR phyllosilicates are not as Fe^{3+}-rich as CM phyllosilicates. CR2 and CR3 spectra are uniformly red-sloped, likely due to the presence of abundant Fe–Ni metal. Absolute reflectance seems to decrease with increasing degree of aqueous alteration, perhaps due to the formation of fine-grained opaques from pre-existing metal. Overall, CR spectra are characterized by widely varying reflectance (4–21% maximum reflectance), weak silicate absorption bands in the 0.9–1.3 μm region, overall red slopes, and the lack of an Fe^{3+}–Fe^{2+} charge transfer absorption band in the 0.65–0.7 μm region.

1. Introduction

Carbonaceous chondrites (CCs) have long been a focus of interest because they represent among the most primitive Solar System materials available for study. There is also an interest in determining their source regions as a guide to understanding the early history and evolution of the Solar System. The presence of carbonaceous compounds in CCs also suggests that these meteorites may have provided some of the building blocks for the evolution of life on the Earth.

We are conducting a wide-ranging study of the spectral reflectance properties of carbonaceous chondrites in order to better understand their spectral properties and diversity, to determine what aspects of their mineralogy are expressed in reflectance spectra, whether spectral differences exist between different CCs groups, and what spectral properties of CCs can be used to identify possible parent bodies. This is the third paper in this series, focusing on CR chondrites. CR chondrites are the third major group of CCs that show evidence of aqueous alteration, with some members categorized as petrographic grades 1 and 2 (Van Schmus and Wood, 1967). Other CCs that show evidence of aqueous alteration include the CI and CM groups, as well as some ungrouped and unique CCs. The CI and CM groups were the subject of earlier papers (Cloutis et al., 2011a, 2011b), and the ungrouped and unique meteorites are the subject of a forthcoming paper.

This study focuses on reflectance spectra of CR powders largely because CR slab spectra are unavailable. We also feel that powder spectra are more relevant for analysis of asteroid spectra, where regolith formation should lead to the production of at least some fraction of a powder. In a previous paper (Cloutis et al., 2011b), we examined both slab and powder spectra of CM chondrites and found that slab spectra are generally darker and more blue-sloped than powder spectra, but that characteristic mafic silicate absorption bands are present in both the powder and slab spectra.

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* Corresponding author. Fax: +1 204 774 4134.

E-mail addresses: e.cloutis@uwinnipeg.ca (E.A. Cloutis), pierre.hudon@mcgill.ca (P. Hudon), takahiro_hiroi@brown.edu (T. Hiroi), gaffey@space.edu (M.J. Gaffey).

[1] Present address: Department of Mining and Materials Engineering, McGill University, 3610 rue Université, Montreal, Quebec, Canada H3A 2B2.

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By this analogy, we expect analysis of CR powder spectra to provide information on absorption bands that may be diagnostic of CR chondrites, regardless of their physical disposition.

The <2.5 μm reflectance spectra of only two CR chondrites, Renazzo and MAC 87300 have been provided in previous published studies of CC reflectance spectra (Hiroi et al., 1993, 1997). In the current study, we have expanded the suite of CR chondrites to 14 members (including meteorites that may not be "true" CRs, but share some characteristics with CRs; e.g., LEW 85332 (Krot et al., 2002). Infrared transmission and reflectance spectra (>2.5 μm) are available for a number of CR chondrites (e.g., Sandford, 1984; Sato et al., 1997; Sato and Miyamoto, 1998; Osawa et al., 2005). As an example of their utility, analysis of these infrared spectra has been used to identify the presence of both olivine and serpentine in Renazzo (Sandford, 1984).

CR chondrites are distinguished from other CC groups using a number of criteria, including abundant, large, multilayered metal-rich type I chondrules, abundant Mg-rich anhydrous mafic silicates, abundant matrix and dark inclusions that contain framboidal magnetite, unique assemblages of serpentine- and chlorite-rich phyllosilicates and carbonates, abundant metal, and low calcium–aluminum inclusion (CAI) abundances (McSween, 1977; Weisberg et al., 1993; Krot et al., 2002).

2. CR composition

2.1. Overview

CRs are among the most reduced of the carbonaceous chondrites with abundant free metal (10–16 wt.%) and magnetite (Kallemeyn et al., 1994) (Table 1). The known CR chondrites range between petrologic grades 1 and $\sim$3. They consist of subequal amounts of matrix and chondrules (Ash and Pillinger, 1992). Silicates comprise between $\sim$85 and 95% of the bulk (Schrader et al., 2011). Whole rock elemental abundances are similar to other CCs (Krot et al., 2002). They can also contain both hydrous and anhydrous mafic silicates (Weisberg et al., 1989; Brearley and Jones, 1998; Krot et al., 2002). The proportion of anhydrous to hydrous silicates decreases from petrologic grade 3 (hydrous silicates rare or nonexistent) to petrologic grade 1 (anhydrous silicates rare or nonexistent). Olivine is the dominant silicate in CR2 and CR3 chondrites, and both olivine and pyroxene are generally Fe-poor ($\lesssim$5 mol.% Fe) (Weisberg et al., 1989; Ash and Pillinger, 1992; Brearley and Jones, 1998; Krot et al., 2002). In CR3 chondrites, the anhydrous silicates are generally Fe-poor and matrix silicates are poorly crystalline or amorphous (Floss and Stadermann, 2009a). Phase abundances for CR chondrites as determined by different investigators are provided in Table 2. Mössbauer analysis of the Fe-bearing components of Renazzo indicates 2.6 wt.% troilite, 28.5 wt.% silicates, and 25.2 wt.% Fe–Ni metal (Bland et al., 2008).

CR chondrites preserve evidence for varying degrees of aqueous alteration, manifested by progressive replacement of anhydrous silicates and chondrule mesostasis by phyllosilicates (Burger and Brearley, 2005). CR2 chondrites contain heavily hydrated matrix and/or matrix lumps composed of serpentine, saponite, sulfides, framboidal or platy magnetite, and carbonates (Krot et al., 2002).

Table 2
Compositions of CR chondrites (vol.%). *Sources of data:* [1] Weisberg et al. (1993) and Kallemeyn et al. (1994). [2] McSween (1979). [3] Burger and Brearley (2005). [4] Schrader et al. (2011).

Phase	Abundance (vol.%)			
Chondrules	48–63	35–60	50–60	31–76
Matrix	30–51	31–57		23–68[b]
Dark inclusions	<8			
Inclusions[a]	0.1–3	1–2		
Metal	5–8		5–8	1–8[c]
Sulfides	1–4			
Lithic fragments		2–3		
Opaque minerals		2–6		5–13
Source of data	1	2	3	4

[a] Refractory inclusions, including olivine aggregates.
[b] Matrix + dark inclusions.
[c] Metal + sulfides.

2.2. Matrix

Fine-grain matrix makes up more than 30% of CRs (Weisberg and Prinz, 2000), and it appears to be compact with only minor porosity (Hezel and Howard, 2010). Most matrix minerals were formed as a consequence of aqueous alteration on the parent body, resulting in infilling of voids and compaction of the matrix (Trigo-Rodriguez et al., 2006; Rubin et al., 2006; Trigo-Rodriguez and Blum, 2009a, 2009b). Broad beam analysis of matrix and dark inclusions gives Fe/(Fe + Mg) ratios of 0.4–0.93 (Weisberg et al., 1993; Zolensky et al., 1993). However, the Fe-rich values probably reflect the fact that CR matrix includes abundant fine-grained and finely-dispersed metal, magnetite and Fe sulfides, as phyllosilicate analyses are generally more Mg-rich (0.4–0.61) than bulk matrix analyses (Weisberg et al., 1993; Zolensky et al., 1993). CR matrix phyllosilicates generally consist of serpentine–saponite intergrowths (as are found in CI chondrites; Brearley and Jones, 1998), and the phyllosilicates appear to be more Fe-rich than those in CI, CM, and CV chondrites (Buseck and Hua, 1993). CR matrix can also contain some aluminous chlorite-like phases, and lacks tochilinite (Buseck and Hua, 1993). Matrix magnetite occurs in the form of framboids and platelets (Weisberg et al., 1989). Olivine is the dominant matrix phase in CR2s and CR3s, and pyroxene, Ca-carbonates, kamacite, taenite, magnetite, pyrrhotite, pentlandite, saponite, and serpentine are also present (Weisberg et al., 1989, 1993; Brearley and Jones, 1998; Zolensky et al., 1993; Kallemeyn et al., 1994). The proportions of these phases vary with degree of aqueous alteration (Krot et al., 2002).

2.3. Mafic silicates

Olivine is characterized by a sharp compositional peak at $Fa_{1.5}$, within a broader cluster from $Fa_{<1}$ to $Fa_{4–6}$ but with a few grains up to $Fa_{\sim 50}$, and there are few olivine grains between Fa_0 and Fa_1

Table 1
Petrographic characteristics of C-chondrite groups. *Sources of data*: Brearley and Jones (1998) and Weisberg et al. (2006).

Group	Chondrule abundance (vol.%)	Matrix abundance (vol.%)	Refractory inclusion abundance (vol.%)	Metal abundance (vol.%)	Chondrule mean diameter (mm)
CI	$\ll$1	>99	$\ll$1	0	–
CM	20	70	5	0.1	0.3
CR	50–60	30–50	0.5	5–8	0.7
CO	48	34	13	1–5	0.15
CV	45	40	10	0–5	1.0
CK	15	75	4	<0.01	0.7
CH	$\sim$70	5	0.1	20	0.02