Spectral reflectance properties of carbonaceous chondrites: 6. CV chondrites

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Abstract

Multiple reflectance spectra of 11 CV chondrites have been measured to determine spectral-compositional relationships for this meteorite class and to aid the search for CV parent bodies. The reflectance of CV chondrite spectra is variable, ranging from ~5% to 13% at 0.56 μm, and ~5% to 15% at the 0.7 μm region local reflectance maximum. Overall slopes range from slightly blue to red for powders, while slab spectra are strongly blue-sloped. With increasing average grain size and/or removal of the fines fraction, CV spectra generally become more blue-sloped. CV spectra are characterized by ubiquitous absorption features in the 1 and 2 μm regions. The 1 μm region is usually characterized by a band centered near 1.05–1.08 μm and a band or shoulder near 1.3 μm that are characteristic of Fe-rich olivine. Band depths in the 1 μm region for powdered CVs and slabs range from ~1% to 10%. The 2 μm region is characterized by a region of broad absorption that extends beyond 2 μm and usually includes band minima near 1.95 and 2.1 μm; these features are characteristic of Fe2+-bearing spinel. The sample suite is not comprehensive enough to firmly establish whether spectral differences exist between CVs, CV OVA X and CV OUV subclasses, or as a function of metamorphic grade. However, we believe that the mineralogic and petrologic differences that exist between these classes, and with varying petrologic subtype (CV 3.0–>3.7), may not be significant enough to result in measurable spectral differences that exceed spectral variations within a subgroup, within an individual meteorite, or as a function of grain size. Terrestrial weathering seems to affect CV spectra most noticeably in the visible region, resulting in more red-sloped spectra for finds as compared to falls. The search for CV parent bodies should focus on the detection of olivine and spinel absorption bands, specifically absorption features near 1.05, 1.3, 1.95, and 2.1 μm, as these are the most commonly seen spectral features of CV chondrites.

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1. Introduction

As part of an ongoing study of the spectral reflectance properties of carbonaceous chondrites (CCs) (Cloutis et al., 2011a,b, Cloutis et al., 2012a–c), in this paper we examine and discuss the spectral properties of VC carbonaceous chondrites. The goals of this larger study include determining relationships between CC reflectance spectra and composition/petrography/mineralogy. We also aim to determine whether variations within a group are expressed spectrally, and whether different CC groups exhibit unique spectral properties.

CV chondrites are of importance and interest to planetary scientists for a number of reasons. For example, the fall of the Allende CV chondrite in 1969 provided many hundreds of kilograms of a single body for detailed analysis. This meteorite has provided the best estimates for the age of the Solar System and timing of formation, from dating of calcium-aluminum inclusions (e.g., Chen and Wasserburg, 1981). CVs also provide insights into possible early Solar System heating events of planetesimals (e.g., Weiss et al., 2010; Elkins-Tanton et al., 2011; Humayun and Weiss, 2011). CVs have also been tentatively linked to a number of possible parent bodies using spectroscopic criteria (e.g., Burbine et al., 2001). More recent studies suggest that other asteroids have similarities to CVs, but with enhancements of some CV components (e.g., Sunshine et al., 2008a,b).

The known CV chondrites are approximately of petrologic grade 3 (McSween, 1977, 1979). CVs are dominated by olivine (>75 vol.%), with lesser amounts of enstatite, plagioclase feldspars, magnetite, sulfides, and metal (Howard et al., 2009). Olivine
composition can vary widely, but is fairly fayalitic (>Fa35) (Weisberg and Prinz, 1997). Phyllosilicates are normally absent or rare, but are abundant in at least one case (Keller et al., 1994).

Reflectance spectra of a suite of 11 CV chondrites have been examined in order to determine the range of spectral properties of this meteorite group, whether they exhibit differences with petrologic subgrade, subtype (CVr, CVox, CVoxA, CVoxB), viewing geometry, and grain size, whether they are spectrally distinct from other CCs, and to provide spectral–compositional guidelines that may be useful in the search for CV parent bodies.

2. Compositional properties of CV chondrites

In general, CV chondrites contain ∼32–67 vol.% chondrules, 6–12 vol.% inclusions, 0–4 vol.% lithic/mineral fragments, 3–8 vol.% opaque minerals, and 17–51 vol.% matrix (McSween, 1977, 1979; Buseck and Hua, 1993). Phyllosilicates, when present, generally occur in small amounts (Buseck and Hua, 1993). Fayalitic olivine and magnetite abundances are positively correlated; magnetite + fayalitic olivine versus metal are inversely correlated (Howard et al., 2009). Their overall composition in comparison to other CC groups is provided in Table 1. A detailed analysis of Allende and a number of other CVs are provided in Tables 2 and 3 and a compilation of CAI abundances in CVs is provided in Table 4.

2.1. Subgroups

The CV3 chondrites have been subdivided into oxidized (CV3Ox) and reduced (CV3R) groups based on their modal metal:magnetite ratios, Ni content of the metal and sulfides (McSween, 1977) and other petrographic and mineralogic criteria (Krot et al., 1995). The oxidized group is further subdivided into two subgroups (Allende-like (CV3OxA) and Bali-like (CV3OxB)) on the basis of alteration features (Weisberg et al., 1997) which are thought to relate to the degree and temperature of aqueous alteration that they experienced (Krot et al., 1998) and other characteristics, summarized in Table 5.

The oxidized and reduced subgroups have different metal versus magnetite abundances. Members of the CV3OxA group have low abundances of Fe–Ni–metal, sulfides and magnetite (Bland et al., 2000). The CV3OxA oxidized subgroup meteorites have variable to high abundances of magnetite but low or absent metal and low sulfides (Bland et al., 2000). The CVR meteorites have intermediate magnetite abundances and high contents of metal and sulfides (Bland et al., 2000). It is suggested that the reduced subgroup may be the precursor to the oxidized subgroup (Howard et al., 2009). Bland et al. (2002) suggested that the reduced and oxidized subgroups may be reflecting some other mineralogic/petrologic effect, as magnetite abundance is higher in Vigarano (a reduced CV) than Allende (an oxidized CV). Magnetite abundances seems to increase from CV3OxA (<0.5 wt.% for Allende), to CV3OxB (2.6–3.2 wt.% for Grosnaja and Mokoia), to CVR (3.8–4.1 wt.% for Leoville and Vigarano) (Bland et al., 2000; see also Tables 3 and 5). A comparison of the phase abundances for CV3R chondrites (specifically Vigarano and Efremovka) and CV3OxA chondrites (specifically Allende, Mokoia, Grosnaja, Kaba) is provided in Table 5.

The CV3OxA subgroup is characterized by the presence of secondary low-Ca phyllosilicates (saponite and Na-phlogopite), magnetite, Ni-rich sulfides, fayalite (Fa>90), and Ca–Fe-rich pyroxenes (Fs10–50 Wo45–50) (Krot et al., 1998). Phyllosilicates replace primary Ca-rich minerals, and magnetite is replaced to varying degrees by fayalite and Ca–Fe–rich pyroxenes (Krot et al., 1998). In CV3OxA chondrites, secondary fayalite and phyllosilicates are virtually absent in chondrules and CAIs. These observations suggest that CV3OxA lithologies experienced higher alteration temperatures than CV3OxB lithologies (Krot et al., 1998). It has been suggested that the sparse phyllosilicates in the oxidized subgroup, represented by Mokoia, were formed from Fe-rich olivine by removal and oxidation of Fe2+ to Fe3+ planar precipitates (Tomoeak and Buseck, 1990). Subsequent hydration formed Fe oxides and

### Table 1

Petrographic characteristics of C-chondrite groups. Source: Brearley and Jones (1998).

<table>
<thead>
<tr>
<th>Group</th>
<th>Chondrule</th>
<th>Matrix abundance (vol.%)</th>
<th>Refractory inclusion abundance (vol.%)</th>
<th>Metal abundance (vol.%)</th>
<th>Chondrule mean diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>&lt;1</td>
<td>&gt;99</td>
<td>&lt;1</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>CM</td>
<td>20</td>
<td>70</td>
<td>5</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>CR</td>
<td>50–60</td>
<td>30–50</td>
<td>0.5</td>
<td>5–8</td>
<td>0.7</td>
</tr>
<tr>
<td>CO</td>
<td>48</td>
<td>34</td>
<td>13</td>
<td>1–5</td>
<td>0.15</td>
</tr>
<tr>
<td>CV</td>
<td>45</td>
<td>40</td>
<td>10</td>
<td>0–5</td>
<td>1.0</td>
</tr>
<tr>
<td>CK</td>
<td>15</td>
<td>75</td>
<td>4</td>
<td>&lt;0.01</td>
<td>0.7</td>
</tr>
<tr>
<td>CH</td>
<td>~70</td>
<td>5</td>
<td>0.1</td>
<td>20</td>
<td>0.02</td>
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</tbody>
</table>

Source of data: Bland et al. (2004).

### Table 2

Modal mineralogy of Allende.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Wt.%</th>
<th>Vol.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine (Fo100)</td>
<td>20.5</td>
<td>23.4</td>
</tr>
<tr>
<td>Olivine (Fo90)</td>
<td>14.6</td>
<td>15.4</td>
</tr>
<tr>
<td>Olivine (Fo80)</td>
<td>20.8</td>
<td>20.6</td>
</tr>
<tr>
<td>Olivine (Fo70)</td>
<td>21.4</td>
<td>20.6</td>
</tr>
<tr>
<td>Olivine (Fo60)</td>
<td>4.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Pentlandite</td>
<td>11.1</td>
<td>8.0</td>
</tr>
<tr>
<td>Clinoenstatite (En90)</td>
<td>5.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Plagioclase (An100)</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Magnetite</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe-metal</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### Table 3

Modal mineralogy and selected phase abundance of CV chondrites.

<table>
<thead>
<tr>
<th>Vol.%a</th>
<th>Allende</th>
<th>Grosnaja</th>
<th>Leoville</th>
<th>Mokoia</th>
<th>Vigarano</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forsterite</td>
<td>22.4</td>
<td>11.0</td>
<td>19.3</td>
<td>24.6</td>
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<tr>
<td>Fo90</td>
<td>7.6</td>
<td>10.8</td>
<td>13.3</td>
<td>18.2</td>
<td></td>
</tr>
<tr>
<td>Fo80</td>
<td>9.4</td>
<td>16.9</td>
<td>21.6</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>Fo70</td>
<td>20.6</td>
<td>10.8</td>
<td>6.1</td>
<td>12.4</td>
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<tr>
<td>Fo60</td>
<td>19.7</td>
<td>15.0</td>
<td>7.3</td>
<td>11.9</td>
<td></td>
</tr>
<tr>
<td>Fo50</td>
<td>1.9</td>
<td>5.8</td>
<td>7.1</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Fo40</td>
<td>1.1</td>
<td>6.3</td>
<td>1.7</td>
<td>2.6</td>
<td></td>
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<tr>
<td>Fayalite</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Enstatite</td>
<td>6.3</td>
<td>4.8</td>
<td>6.3</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>Anorthite</td>
<td>1.1</td>
<td>1.3</td>
<td>1.7</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Magnetite</td>
<td>0.3</td>
<td>1.6</td>
<td>2.6</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Sulfide</td>
<td>6.6</td>
<td>7.9</td>
<td>8.1</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Fe–Ni metal</td>
<td>1.0</td>
<td>0.8</td>
<td>1.1</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Fe-oxide</td>
<td>0.0</td>
<td>2.7</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Phyllosilicate</td>
<td>1.9</td>
<td>4.2</td>
<td>3.7</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Magnetiteb</td>
<td>&lt;0.5 wt.%</td>
<td>8.0 wt.%</td>
<td>3.8 wt.%</td>
<td>3.2 wt.%</td>
<td>4.1 wt.%</td>
</tr>
<tr>
<td>Troilite</td>
<td>11.4</td>
<td>16.9</td>
<td>10.8</td>
<td>13</td>
<td>23.6</td>
</tr>
<tr>
<td>Silicatesc</td>
<td>87.7</td>
<td>62.4</td>
<td>56</td>
<td>67.5</td>
<td>51.2</td>
</tr>
<tr>
<td>Fe-Nic</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>4.9</td>
</tr>
<tr>
<td>Magnetitec</td>
<td>n.d.</td>
<td>11.8</td>
<td>16.4</td>
<td>15.6</td>
<td>14.7</td>
</tr>
<tr>
<td>Paramagc</td>
<td>0.9</td>
<td>5.9</td>
<td>16.7</td>
<td>3.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Note: only includes phases present at >1 wt.%. Analysis performed on samples free of large inclusions, such as CAIs and dark inclusions. A number of CVs also contain glassy mesostasis within chondrules, which was not included in the totals. a Source of data: Howard et al. (2010); abundances determined by PSD-XRD. b Bland et al. (2000). c Bland et al. (2008); numbers indicate proportions of Fe in different phases as a fraction of total Fe; paramag = paramagnetic component.
hydroxides, while the Fe-poor olivine was altered to saponite (Tomoeaka and Buseck, 1990).

In general, CV$_R$ chondrites show the least evidence of either aqueous alteration or metasomatism; the CV$_{DOA}$ chondrites primarily show evidence of metasomatism; the CV$_{DIA}$ chondrites appear to have been most affected by aqueous alteration (Keller et al., 1994; Krot et al., 1995; Brearley, 2006; Huss et al., 2006). Howard et al. (2010) found that mineralogic parameters, such as the abundances of fayalite, ferrous olivine, and magnetite overlap between the CV$_R$ and CV$_{DIA}$ groups, and show no relationship to petrographic type. These mineralogic relationships also show no correlation to petrographic type. These mineralogic relationships also show no correlation to petrographic type; in addition, Allende is distinct from other CV$_R$ chondrites, different criteria lead to different petrologic subtypes. For example, infrared spectroscopic categories of insoluble organic matter in CV$_R$s do not correlate with degree of metamorphism determined by other means (Kebukawa et al., 2011).

Bonal et al. (2006) used Raman spectroscopic properties of organic matter in the matrix, as well as petrographic information, to derive petrologic subgradients for a variety of CV$_R$s. They determined that the induced thermoluminescence approach used by Guimon et al. (1995) underestimated petrologic grades for a number of CV$_R$s common to both studies. The derived petrologic subgrades from Bonal et al. (2006) are provided in Table 6. Fries et al. (2011) determined, from Raman spectroscopy of organic material in a variety of CCs, that Vigarano is more metamorphosed than Kainsaz (a CO$_3.2$ chondrite).

### 2.2.1. Matrix

Matrix comprises between 17 and 51 vol.% of CV$_R$s, and is composed of olivine (the dominant phase), minor pyroxene (Fs$_{10-50}$ Wm$_{50}$), kamacite, taenite, magnetite (minor), pyrrhotite, pentlandite, Ca-phosphates (minor), nepheline (minor), sodalite (minor), micas (minor, only in chondrules), saponite (minor), amorphous material, and carbonates (in chondrules only) (Buseck and Hua, 1993; Zolensky et al., 1993). Fayalitic olivine (Fa$_{35}$) comprises up to 80 vol.% of CV$_R$ matrix (Kojima and Tomezko, 1996; Weisberg and Prinz, 1997; Krot et al., 1998). While most matrix olivine is Fa$_{35}$, its composition can range from Fa$_{10}$ to Fa$_{25}$ (Buseck and Hua, 1993; Zolensky et al., 1993). CV$_R$ matrix appears to consist of at least two end-member types, at least texturally (Hurt et al., 2012).

### 2.2.2. Chondrules

Chondrules, which occupy 32–65 vol.% of CV$_R$s are generally of two main types: I and II. Type I chondrules are olivine-rich and Fa$_{10}$, but can range up to Fa$_{25}$ (McSween, 1977; Brearley and Jones, 1998). Type I chondrules occur as two main subtypes: opaque mineral-poor and opaque mineral-rich, and occur in approximately equal abundances: the opaques are commonly metal, magneteite and/or sulfide minerals (McSween, 1977). Type II chondrules are rare, and contain more Fe-rich olivine, as well as fine-grained chromite (Johnson and Prinz, 1991).
2.2.3. Mafic silicates
Fayalitic olivine (average \(\text{Fa}_{-32}\)) is a major component of the matrices and dark inclusions of CV3 chondrites (Weisberg and Prinz, 1998). It commonly occurs as rims, veins and halos in and around chondrule silicates in \(\text{CV3}_{\text{pha}}\) chondrites and to a much lesser extent in \(\text{CV3}_{\text{R}}\) and \(\text{CV3}_{\text{OxA}}\) chondrites (Weisberg and Prinz, 1998). Fayalitic olivine makes up >80% of the matrix of Allende (Weisberg and Prinz, 1998). The range of \(\text{Fe}\) content varies, likely as a result of equilibration (Brearley and Jones, 1998). XRD data suggest that olivines span the entire \(\text{Fe-Mg}\) range, and all CVs contain a component (4–13%) of fine-grained olivine that is \(\text{Fa}_{>60}\) (Howard et al., 2009).

2.2.4. CAIs
The average areal abundance of CAIs in CV chondrite varies among different studies (Table 4), ranging from 0.65 area% to 9.4 vol.%. McSween (1977) determined the modal distribution of two types of inclusions: amoeboid olivine inclusions (AOIs) and Ca, Al-rich. AOI abundances range from 1.2–8.6 vol.%; ~2 vol.% in Allende, although higher abundances are seen in other CVs (Grossman and Steele, 1976), while CAI abundances range from 0.3 to 9.4 vol.%. AOIs consist predominantly of olivine (\(\text{Fa}_1-\text{Fa}_{36}\)), as well as pyroxene, nepheline, and sodalite, with rare anorthite, spinel (2.1–13.4% \(\text{FeO}\)), and perovskite (Grossman and Steele, 1976). Alteration of CAIs in \(\text{CV3}_{\text{pha}}\) chondrites includes entry of \(\text{Fe}\) into spinels (Krot et al., 1995).

Two main types of CAIs occur in CVs: type A and B. Type A inclusions include compact and fluffy varieties (MacPherson and Grossman, 1984). Compact type A inclusions are composed of 80–85% mellite (<1% \(\text{FeO}\)), 15–20% spinel (0–4.5% \(\text{FeO}\), mostly 0–1% \(\text{FeO}\)), 1–2% perovskite, and rare plagioclase, hibonite, wollastonite, and grossularite (Grossman, 1975). Clinopyroxene that may be present is restricted to thin rims around inclusions or cavities in their interiors. Fluffy type A inclusions are composed of Al-rich mellite (<0.5% \(\text{FeO}\)), spinel (commonly \(\text{V-rich}\); 0–20% \(\text{FeO}\), mostly <2% \(\text{FeO}\)), perovskite, and hibonite (MacPherson and Grossman, 1984).

Type B inclusions, that occur exclusively in CV chondrites, are composed of abundant fassaite (30–60 vol.%; <1–8% \(\text{FeO}\), <1–18% \(\text{TiO}_2\)), anorthite (5–25 vol.%; \(\text{An}_{90-100}\)), spinel (15–30 vol.%; <1–20% \(\text{FeO}\), mostly <1% \(\text{FeO}\)), and mellite (5–20 vol.%; <1% \(\text{FeO}\)) (Grossman, 1975, 1980; Cloutis and Gaffey, 1993 and references therein).

CAIs are commonly rimmed by other materials. These include Wark-Lowering rings that consist of multiple layers of varying proportions of spinel, perovskite, hibonite, olivine, anorthite, pyroxene, and andradite (Wark and Lowering, 1977). Rim compositions differ from the adjacent matrix and CAI cores, and also differ between Type A and B CAIs, and between fluffy and compact CAIs (Wark and Lowering, 1977).

Additional rimming materials consist of dark, fine-grained materials that mantle peripheries of clasts, inclusions, and chondrules (King and King, 1981; MacPherson et al., 1985). These mantles are multilayered and differ slightly from the matrix in terms of grain size, mineralogy, and chemistry (MacPherson et al., 1985). These “accretionary rings” consist largely of olivine, with lesser amounts of \(\text{Fe}\)-bearing pyroxenes, andradite, nepheline, and iron sulfides (MacPherson et al., 1985) and may be gradational with the surrounding matrix (King and King, 1981).

2.2.5. Dark inclusions
Dark inclusions, at the few vol.% level, are present in CV chondrites and differ slightly, both compositionally and petrographically, from the host meteorite (Fruland et al., 1978). They consist largely of \(\text{FeO}\)-rich olivine (\(\text{Fa}_{0.45}\)) and \(\text{Ca-Fe}\) pyroxene (Fruland et al., 1978; Brearley and Jones, 1998). Dark inclusions are also frequently rimmed (Fruland et al., 1978) and likely underwent a different history of alteration than the surrounding matrix (Johnson et al., 1990; Ohnishi and Toioka, 2002; Fries et al., 2005a,b). Different types of dark inclusions (e.g., Johnson et al., 1990) indicate that they may have undergone aqueous alteration and subsequent dehydration, some may be fragments of primitive accreted materials, and some experienced higher thermal metamorphism than the host meteorite (Bischoff et al., 2006, and references therein). They may have undergone some level of processing prior to their incorporation into the CV host (Johnson et al., 1990). Raman spectroscopy of dark inclusions indicates that their carbon is more graphitic, and hence likely more thermally metamorphosed, than carbon in adjacent matrix (Fries et al., 2005b).

2.2.6. Thermally metamorphosed clasts
Jogo and Krot (2010) and Jogo et al. (2011) reported the presence of thermally metamorphosed CV-type clasts in the Mokoia and Y-86009 CV breccias. The identified clasts contain a variety of textural and mineralogic features that suggest strong prolonged thermal metamorphism or annealing on a CV parent body.

2.2.7. CV breccias
A number of CVs contain clasts that differ from their host meteorites. Such breccias can include mixtures of \(\text{CV}_4\) and \(\text{CV}_0\), materials, and CV clasts of different metamorphic grades (Bischoff et al., 2006, and references therein). Some of the CVs included in this study (e.g., Mokoia, Vigarano) are regolith breccias, containing different types of clasts (e.g., Krot et al., 1998, 2000).

2.2.8. Opaque minerals
The opaque mineralogy differs between the oxidized and reduced subgroups. In \(\text{CV}_4\) chondrites, metal and pyrrhotite are the dominant phases, while in \(\text{CV}_0\), chondrites metal is rare and magnetite is the dominant phase (McSween, 1977; Brearley and Jones, 1998). Opaque phases generally occur in chondrules rather than matrix (McSween, 1977). It also appears that average magnetite grain size increases with increasing thermal metamorphism (Emmerton et al., 2011).

2.2.9. Carbon and carbonaceous phases
Besides metal, magnetite, and sulfides, the major opaque phase in CVs is carbonaceous material. Carbon abundance in CVs ranges from 0.01 to 1.5 wt.% (Pearson et al., 2006; Alexander et al., 2007), and decreases with increasing metamorphic grade (Guimon et al., 1995). The insoluble organic matter in CVs has generally lower H/C, N/C, and O/C ratios than other CCs (Alexander et al., 2007). CVs also contain well-crystallized graphite and carbonaceous globules that are consistent with thermal metamorphism (Aoki and Akai, 2008), as are changes in various other organic compounds (Aponte et al., 2011). Carbon in CVs occurs in a variety of forms, including small (~10 μm) inclusions in chondrules (Fries et al., 2005a). Carbon in chondrules seems to have been more thermally metamorphosed than the carbon in CV matrix (Fries and Bharatia, 2010). Well-ordered graphite is more prevalent in CVs that seem to have experienced higher degrees of thermal metamorphism (Aoki and Akai, 2008). H/C ratios for insoluble organic matter are suggestive of lower values in \(\text{CV}_4\) versus \(\text{CV}_0\) (Alexander et al., 2007). Infrared spectra of CV insoluble organic matter differ from the material from low petrographic type CI, CM, CR and CO chondrites, and are consistent with more condensed aromatics formed by thermal metamorphism (Kebukawa et al., 2011).

2.2.10. Aqueous alteration and secondary minerals
Aqueous alteration in CVs ranges from extremely minor (e.g., Mokoia, Grosnaja, Vigarano) to highly altered with extensive development of phyllosilicates (e.g., Balli) (e.g., Brearley and Jones, 1998; Gyollai et al., 2011), distinct aqueously altered clasts.
(e.g., Tomeoka and Ohnishi, 2011), and can also be variable within a single meteorite (Noguchi et al., 2003; Komatsu et al., 2008). The phyllosilicate mineralogy of CV3 chondrites is dominated by low-Al fine-grained saponites (Fe/(Fe + Mg) = 0–0.2), and various micas (Keller and Buseck, 1990b; Keller and McKay, 1993); serpentine and chlorite are also present in Grossna (Keller and McKay, 1993). The saponite may be associated with fine-grained magnetite (Brearley and Jones, 1998). Ferric iron (at least in the tetrahedral sites of phyllosilicates) was inferred from stoichiometric analysis of Mokoia phyllosilicates (Cohen et al., 1983). Mössbauer analysis of Allende indicates that 10% of the total iron is present as Fe$^{3+}$, presumed to be present in phyllosilicates (Fisher and Burns, 1991). Keller (2011) described an aqueously altered CV (MIL 090001: CV$_a$) containing abundant metal and magnetite, as well as highly altered matrix containing serpentine and chlorite; they tentatively classified this meteorite as a CV2, suggesting that aqueous alteration has extensively affected some CV chondrites.

3. Experimental procedure

Many of the details of our experimental procedure have been discussed in previous papers in this series (Cloutis et al., 2011a,b). A total of 11 CVs, including members of the CV$_{ox}$, CV$_{oxa}$, and CV$_a$ subgroups were included in this study (Table 6). As in our previous studies of CCs, we have applied continuum removal to the spectra to isolate absorption features of interest and use various metrics of spectral slope and overall reflectance to search for systematic spectral–composition trends (Cloutis et al., 2011a,b). Descriptions of the CVs are provided in Appendix A. The various reflectance spectra included in this study are available as an online supplement.

Reflectance spectra used in this study were measured at the RELAB facility at Brown University (Pieters, 1983) at $i = 30^\circ$ and $e = 0^\circ$ and a 5 nm spectral sampling interval and spectral resolution of <5 nm), from 0.3 to 2.6 μm, and at the PSF facility at the University of Winnipeg at $i = 30^\circ$ and $e = 0^\circ$ and 1 nm spectral output, from 0.35 to 2.6 μm. Some older spectra from Gaffey (1974) were digitized and are available through the RELAB archive. The RELAB and PSF spectra were measured relative to halon or Spectralon® and corrected for minor irregularities in the reflectance of these standards in the 2 μm region. It should be noted that in the ensuing discussion we have minimized comparisons of absolute reflectance and spectral slopes between spectra measured using bidirectional reflectance versus those measured using an integrating sphere (Gaffey, 1974), as these parameters are dependent on observational conditions (Gradie et al., 1980; Gradie and Veverka, 1982, 1986). We also note that sample preparation procedures for the powders differed somewhat between Gaffey (1974) and this study. For the RELAB and PSF measurements, a powdered sample is poured into an aluminum cup and the edge of a glass slide is drawn across the sample to produce a flat surface. In all cases, a flat powdered surface is used for the spectral measurements.

We have developed a variety of easily-applicable spectral metrics for analysis of CCs (Cloutis et al., 2011a,b), and we utilize these same metrics for analysis of CVs. These metrics include absolute reflectance at the visible region peak, highest absolute reflectance, various measures of overall spectral slope, band area ratios, and band depths (Cloutis et al., 1986, 2011b). Absorption features in the 1 μm region were isolated by fitting a straight line continuum that is tangent to the reflectance spectrum on either side of this region. Absorption features in the 2 μm region were isolated by fitting a straight line continuum that is tangent to the reflectance spectrum at the interband peak near 1.5 μm and the long wavelength end fixed at 2.5 μm. Band centers in this region were determined using a combination of chords constructed across the feature and polynomial fitting. Band depths were calculated using Eq. 32 of Clark and Roush (1984). Band area ratios (BARs) were calculated using procedures first outlined in Cloutis et al. (1986): band II/IA and band II/II band.

4. Spectral properties of constituent phases

The spectral reflectance properties of most CV chondrite constituents have been discussed in previous papers in this series. The main minerals that are expected to affect CV reflectance spectra are olivine, Fe-bearing pyroxene, spinel, melilitie, metal, magnetite, and carbonaceous phases.

Briefly, olivine exhibits an absorption feature consisting of a central band near 1.05 μm (due to crystal field transitions in Fe$^{2+}$ located in the M2 site) and side bands near 0.85 and 1.3 μm due to crystal field transitions in Fe$^{2+}$ located in the M1 site. The position of this feature moves from ~1.045 to ~1.085 μm with increasing Fe$^{2+}$ content (King and Ridley, 1987). Low-Ca pyroxene exhibits two strong absorption bands near 0.9 (band I) and 1.9 μm (band II) due to crystal field transitions in Fe$^{2+}$ located in the pyroxene M2 site; weaker bands may also be present near 0.9 and 1.2 μm when Fe$^{2+}$ is located in the M1 site (Adams, 1974). With increasing Fe$^{2+}$ and Ca content, the M2 bands move to longer wavelengths, ranging from ~0.90 to 0.94 μm (band I) and ~1.80 to 2.08 μm (band II) for low-Ca pyroxenes, and ~0.93 to 1.08 μm (band I) and ~1.90 to 2.37 μm (band II) for high-Ca pyroxenes (Adams, 1974; Cloutis and Gaffey, 1991; Klima et al., 2007). Fassaite has a Fe$^{2+}$–Fe$^{3+}$ charge transfer band in the 0.75 μm region, and M1 Fe$^{2+}$ crystal field transition bands near 0.95 and 1.15 μm (Cloutis and Gaffey, 1991). Spinel has a strong absorption band near 2 μm due to tetrahedrally coordinated Fe$^{2+}$ crystal field transitions (Cloutis et al., 2004). Mellilitie has an absorption feature in the 1.6–2.0 μm region attributable to crystal field transitions in tetrahedrally coordinated Fe$^{2+}$. Meteoritic metal has a red-sloped and otherwise featureless spectrum (Cloutis et al., 2010), although chondritic metal appears to be flat-sloped (Gaffey, 1986). Magnetite has a broad absorption band in the 1 μm region due to crystal field transitions in octahedrally coordinated Fe$^{2+}$ (Sherman et al., 1982). Carbonaceous phases may be flat or red-sloped depending on structure and composition (Cloutis et al., 2011a,b). Reflectance spectra of a number of constituent CV phases are shown in Fig. 1.

5. Results

Our analysis of CVs includes a variety of grain sizes for a number of the CVs, duplicate spectra, spectra of separate splits, and whole rock spectra (Table 7). We also include CV spectra measured by previous investigators in our analysis (Table 8). However, the number of individual CVs is limited (Table 7), therefore we may not capture the full range of CV spectral variability, and the number of CVs in the various subgroups is also limited.

5.1. Spectra of CV3, CV$_{ox}$, CV$_{oxa}$, CV$_{oxb}$, and CV$_{ox}$

Our survey and analysis of CV spectra focuses on powdered samples because they will likely be the most representative of the spectral properties of CV parent bodies, which are expected to have powdered regoliths (Dollfus, 1981, 1971; Dollfus et al., 1975). Of the 11 available CVs, three are only described as CV3 without subgroups. Their reflectance spectra are shown in Fig. 2a. With only limited information on these samples, it is difficult to make any firm observations. ALHA 81003 has been assigned a low petrologic subtype (3.0) by Bonal et al. (2006) and has lower overall reflectance than the other two CVs, for which petrographic
integrating sphere (Gaffey, 1974). Both are red-sloped, in contrast
mum grain size and the fact that Mokoia was measured using an
similar overall reflectance, in spite of a small difference in maxi-
phosed (>CV3.6), and Mokoia is
Bonal et al. (2006)suggested that Allende is much more metamor-
carbon black (grain sizes indicated for each).

Three of our CVs (ALH 84028, Allende, and Mokoia) have been
categorized as subtype CV3OxA, and their spectra are shown in
Fig. 2b. Guimon et al. (1995)classified them all as CV3.2, although
Bonal et al. (2006) suggested that Allende is much more metamor-
phosed (>CV3.6), and Mokoia is ~CV3.6. Mokoia and Allende have
similar overall reflectance, in spite of a small difference in maxi-
mum grain size and the fact that Mokoia was measured using an
integrating sphere (Gaffey, 1974). Both are red-sloped, in contrast
to ALH 84028 which is neutral to blue-sloped. All three spectra ex-
hibit an absorption band in the 1 \( \mu \)m region, near 1.05 \( \mu \)m for ALH
84028 and Allende, while Mokoia shows two apparent absorption
features near 0.87 and 1.05 \( \mu \)m. This feature is most con-
istent with spinel, as discussed below.

Table 7
CV reflectance spectra included in this study.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Sample type</th>
<th>grain size</th>
<th>RELAB or PSF file ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALH 81003</td>
<td>&lt;125 ( \mu )m</td>
<td>c1m116</td>
<td></td>
</tr>
<tr>
<td>ALH 84028</td>
<td>&lt;125 ( \mu )m</td>
<td>c1mb78, c2mb78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;25 ( \mu )m</td>
<td>camb78</td>
<td></td>
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<tr>
<td></td>
<td>25–45 ( \mu )m</td>
<td>cbm78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45–75 ( \mu )m</td>
<td>ccmb78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75–125 ( \mu )m</td>
<td>cdmb78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;500 ( \mu )m</td>
<td>c1mc05</td>
<td></td>
</tr>
<tr>
<td>ALH 85006</td>
<td>&lt;125 ( \mu )m</td>
<td>c1m46</td>
<td></td>
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<tr>
<td>Allende</td>
<td>Roughened slab (6 spots)</td>
<td>120215a.001-006</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;125 ( \mu )m</td>
<td>120216a.022, 120216a.023</td>
<td></td>
</tr>
<tr>
<td>CAI unsorted powder</td>
<td>90814c.009, 90814a.010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mokoia</td>
<td>&lt;150 ( \mu )m (with mask)</td>
<td>120216a.001, 120216a.009</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;180 ( \mu )m</td>
<td>camb57, cbm57</td>
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<td></td>
<td>&lt;150 ( \mu )m</td>
<td>mgp124</td>
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<td></td>
<td>&lt;45 ( \mu )m</td>
<td>s1rs40</td>
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</tr>
<tr>
<td></td>
<td>&lt;1000 ( \mu )m</td>
<td>c1s746</td>
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<tr>
<td></td>
<td>&lt;125 ( \mu )m</td>
<td>c2mb63</td>
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<td></td>
<td>&lt;63 ( \mu )m</td>
<td>c3mb63</td>
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</tr>
<tr>
<td></td>
<td>63–125 ( \mu )m</td>
<td>c4mb63</td>
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</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 400 ( \mu )C</td>
<td>camb63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 500 ( \mu )C</td>
<td>cbm63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 600 ( \mu )C</td>
<td>ccmb63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 700 ( \mu )C</td>
<td>cbm63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 800 ( \mu )C</td>
<td>cem63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 900 ( \mu )C</td>
<td>cbm63</td>
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</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 1000 ( \mu )C</td>
<td>cbm63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 1100 ( \mu )C</td>
<td>cbm63</td>
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</tr>
<tr>
<td></td>
<td>&lt;63 ( \mu )m, 1200 ( \mu )C</td>
<td>cbm63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500–2000 ( \mu )m (JFB-01)</td>
<td>120216a.006, 120216a.014</td>
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<td>1–&gt;2000 ( \mu )m (JFB-02)</td>
<td>120216a.005, 120216a.013</td>
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</tr>
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<td>75–250 ( \mu )m (JFB-03)</td>
<td>120216a.008, 120216a.016</td>
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</tr>
<tr>
<td></td>
<td>&lt;150 ( \mu )m (JFB-04)</td>
<td>120216a.007, 120216a.015</td>
<td></td>
</tr>
<tr>
<td>Grosnaja</td>
<td>&lt;75 ( \mu )m</td>
<td>mgp128</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75–150 ( \mu )m</td>
<td>mgp130</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150–500 ( \mu )m</td>
<td>mgp132</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;45 ( \mu )m</td>
<td>s1rs43</td>
<td></td>
</tr>
<tr>
<td>Leoville</td>
<td>&lt;150 ( \mu )m</td>
<td>mgp134</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;150 ( \mu )m (with mask)</td>
<td>091104a.017, 091104a.018</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;150 ( \mu )m</td>
<td>120216a.004, 120216a.012</td>
<td></td>
</tr>
<tr>
<td>Mokoia</td>
<td>&lt;150 ( \mu )m</td>
<td>mgp136</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;150 ( \mu )m (with mask)</td>
<td>90814c.011, 90814c.012</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;150 ( \mu )m</td>
<td>120216a.002, 120216a.010</td>
<td></td>
</tr>
<tr>
<td>NWA 3118</td>
<td>&lt;125 ( \mu )m</td>
<td>c1mp129</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;125 ( \mu )m, dark inclusion</td>
<td>c1mp130</td>
<td></td>
</tr>
<tr>
<td>QUE 93744</td>
<td>&lt;75 ( \mu )m</td>
<td>c1p141</td>
<td></td>
</tr>
<tr>
<td>Vigarano</td>
<td>&lt;150 ( \mu )m</td>
<td>mgp138</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;100 ( \mu )m</td>
<td>c1mb59</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;150 ( \mu )m (with mask)</td>
<td>90817b.002, 90817b.003</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;150 ( \mu )m</td>
<td>120216a.003, 120216a.011</td>
<td></td>
</tr>
<tr>
<td>Y-86751</td>
<td>&lt;125 ( \mu )m</td>
<td>c1mp09</td>
<td></td>
</tr>
</tbody>
</table>

Note: “mngp0xx” spectra were acquired with an integrating sphere (Gaffey, 1974) and have been subsequently digitized; all other spectra were acquired at \( \iota = 30^{\circ} \) and \( e = 0^{\circ} \).
of reflectance, with an overall neutral to blue slope (Fig. 2d), and in contrast to the other CV spectra, have less well-defined absorption bands in the 1 and 2 μm regions. One possibility is that the lack of well-defined mafic silicate absorption bands is due to their lower abundance of Fe-bearing silicates compared to other CVs (Bland et al., 2008; Table 3).

5.2. Metamorphic subtypes

The CV spectra can also be compared on the basis of metamorphic subtype. As has been found for other CCs, we expect increasing metamorphism to lead to increasing reflectance, bluer slopes, and better-defined mafic silicate absorption bands due to aggregation/loss of organics, and crystallization of amorphous/poorly crystalline silicates. It is also possible that metal/silicate re-equilibration could lead to incorporation of iron into the silicates. Fig. 3a shows spectra of powdered CVs along with the available subtypes as determined by Guimon et al. (1995) and Bonal et al. (2006). Besides the aforementioned difference in slope between the reduced and oxidized groups, there appears to be no systematic variation as a function of metamorphic subtype, even when the oxidized and reduced subgroups are separated. The 1 μm continuum-removed spectra (Fig. 3b) do not show any systematic relationships between band depths or positions with petrographic subtype. Most of these CVs show band minima near the expected position for olivine (N/C24 1.05 μm), while Vigarano (CV3.0–3.4) shows a longer than expected band minimum. The 2 μm region continuum-removed spectra (Fig. 3c) show much more diverse behavior. Well-resolved spinel absorption features near 1.95 and 2.1 μm are not present in all the spectra. An absorption feature in the 2.4 μm region of some of the spectra may be attributable to fassaite (Rajan and Gaffey, 1984).

Table 8

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Sample type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALH 84028</td>
<td>&lt;125 μm (0.3–2.5 μm)</td>
<td>1</td>
</tr>
<tr>
<td>Allende</td>
<td>&lt;75 μm (0.6–2.5 μm)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>&lt;125 μm (0.3–2.5 μm)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>&lt;150 μm (0.35–2.5 μm)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Carbonaceous extract (0.35–2.5 μm)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Room temp, 800 °C (IW + 2; IW – 1), &lt;100 μm (0.2–2.5 μm)</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>White inclusions on slab (0.6–2.5 μm)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>AOIs, fluffy type A CAI, type B CAI, CAI-free matrix, bulk; all &lt;38 μm (0.3–2.5 μm)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>&lt;74 μm (0.35–2.5 μm)</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>3–150 μm (0.45, 0.55, 0.65, 0.70, 0.95 μm)</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>&gt;150 μm (0.5–2.5 μm)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>&lt;100 s of μm (0.633 μm)</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Solar furnace condensates (0.45–2.5 μm)</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>&lt;45 μm, 45–75 μm, 75–150 μm (0.4–0.6 μm)</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>&lt;75 μm (0.4–1.2 μm)</td>
<td>14, 15, 16</td>
</tr>
<tr>
<td>Grosnaja</td>
<td>&lt;150 μm (0.35–2.5 μm)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>147–495 μm (0.35–2.5 μm)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>74–147 μm (0.35–2.5 μm)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>&lt;74 μm (0.35–2.5 μm)</td>
<td>4</td>
</tr>
<tr>
<td>Leoville</td>
<td>&lt;150 μm (0.35–2.5 μm)</td>
<td>3</td>
</tr>
<tr>
<td>Mokoia</td>
<td>&lt;150 μm (0.35–2.5 μm)</td>
<td>3</td>
</tr>
<tr>
<td>Vigarano</td>
<td>&lt;150 μm (0.35–2.5 μm)</td>
<td>3</td>
</tr>
</tbody>
</table>

If we limit our analysis to CV spectra of a common grain size (<150 μm) acquired with an integrating sphere (Gaffey, 1974), we find that the two most metamorphosed CVs (Bonal et al., 2006) are more red-sloped (Fig. 3d), opposite the expectation of bluer slopes with increasing metamorphism. Bluer slopes are expected as carbonaceous phases become increasingly condensed and C-rich (Cloutis, 2003). Overall reflectance also does not correlate with metamorphic grade. The 1 μm region continuum-removed spectra (Fig. 3e) show no systematic variations with metamorphic grade; absorption features near 0.87–0.90 may be artifacts, as they do not appear in RELAB and PSF CV spectra. The 2 μm continuum-removed spectra (Fig. 3f) all have a broad, shallow, and generally featureless absorption feature, and no apparent correlations of depth with metamorphic grade.

The Gaffey (1974) samples were re-measured at the PSF for this study. Their reflectance spectra (Fig. 3g) vary from red- to blue-sloped, but there is no systematic relationship between absolute reflectance or slope with metamorphic grade. The continuum-removed 1 μm region spectra all show an olivine-associated absorption band in the 1.30–1.35 μm region (similar to the Gaffey (1974) spectra. Band minima are at generally longer wavelengths than for pure olivine, suggesting either an inappropriate continuum or spectral contributions from other phases; other possible phases include amorphous or poorly crystalline Fe-bearing phases,

---

**Fig. 3.** Reflectance spectra for CVs for which subtypes have been determined by Guimon et al. (1995) and Bonal et al. (2006). (a) RELAB powder bidirectional spectra. (b) Same as (a) for continuum-removed 1 μm region. (c) Same as (a) for continuum-removed 2 μm region. (d) CV spectra measured by Gaffey (1974) with an integrating sphere and digitized by RELAB. (e) Same as (d) for continuum-removed 1 μm region. (f) Same as (d) for continuum-removed 2 μm region. (g) Gaffey (1974) samples remeasured at PSF in bidirectional (i = 30°, ε = 0°) mode. (h) Same as (g) for continuum-removed 1 μm region. (i) Same as (g) for continuum-removed 2 μm region. Linear vertical offsets applied to continuum-removed spectra are indicated in brackets on the relevant figures.
magnetite, or fassaite. The 2 µm continuum-removed spectra all show evidence of spinel absorption features near 1.95 and 2.1 µm; band depths do not appear to be correlated with metamorphic grade, however. The lack of systematic spectral variations with metamorphic grade is likely attributable to limited number of CVs, grain size variations, heterogeneities within any CV, and disagreements on degree of metamorphism (Bonal et al., 2006).

### 5.3. Duplicate spectra

Duplicate spectra are available for a number of the CVs, all involving the same split, with some comparative measurements available for bidirectional versus integrating sphere. Duplicate spectra allow us to explore spectral variability within individual CV chondrite subsamples.

Fig. 4a and b shows six ~8 mm diameter spots on a slab of the Allende CV chondrite that were spectrally characterized. No effort was made to target specific phases in the slab. The reflectance spectra are all strongly blue-sloped with peak reflectance near 0.55–0.65 µm and with maximum reflectance ranging from 8.6% to 10.5%. The cause of a blue slope in solid samples is not yet well understood. All the spectra exhibit absorption features in the 1 and 2 µm regions that show little variation from spot to spot. The 1 µm region continuum-removed spectra (Fig. 4c and d) are consistent with Fe-rich olivines: an absorption band centered near 1.05–1.07 µm, an inflection near 0.85 µm, and a better-defined absorption band near 1.3 µm. The well-defined nature of this latter feature is characteristic of ferrous olivines (King and Ridley, 1987). The 2 µm region continuum-removed spectra (Fig. 4e and f) exhibit absorption features near 1.95 and 2.1 µm. The 1.95 µm feature may be attributable to hydrated phases (which are rare in Allende) or, more likely, to Fe²⁺-bearing spinels in CAIs (Cloutis et al., 2004). This phase would also account for the 2.1 µm feature and overall broadness of the 1.9–2.1 µm interval.

Duplicate spectra of <125, <150, <180, 75–250, 500–2000, and 0–>2000 µm fractions of Allende are also available for comparison. The <125 µm fraction spectra (Fig. 4g) are very similar: both are red-sloped and exhibit 1 and 2 µm region absorption features. The continuum-removed spectra show a few differences. The 1 µm region spectra (Fig. 4h) all show the expected olivine absorption features near 1.07 and 1.3 µm, with some differences in the appearance of these bands in terms of the width of the band minimum and intensity of the 1.3 µm band. The 2 µm region spectra (Fig. 4i) are broadly similar to each other and to other slab and powder Allende spectra, with a broad absorption feature centered near 2.1 µm, and an additional feature near 1.95 µm. Two of the spectra also show evidence of weak bands near 1.67 and 2.35 µm, that may be attributable to the carbonaceous phases in the sample or organic contaminants (as the history of this sample is unknown).
The two <180 μm fraction spectra (Fig. 4m) are similar in overall shape, but differ by ~1% in absolute reflectance. The continuum-removed spectra (Fig. 4n and o) are again consistent with olivine, although the 1.3 μm absorption feature is less apparent in these spectra. The 2 μm region shows the expected broad absorption band centered near 2.1 μm, but the spectra are noisier than other Allende spectra.

Coarser-grained Allende duplicate powders spectra are shown in Fig. 4p. The two sets of powders, with grain sizes of 500–2000 μm and 0–>2000 μm exhibit well-resolved olivine and spinel absorption bands. The sample with the finest fraction removed (JFB-01; 500–2000 μm) is more blue-sloped. The spectra have variable overall reflectance, likely attributable to differences in grain size distributions at the surfaces of the samples between duplicate runs (the sample cups were emptied and repacked for the duplicate measurements). Two other sets of Allende powders (Fig. 4q), with sizes of 75–250 μm and >150 μm show little variability within each pair, with overall reflectance varying by <1% absolute reflectance.
between duplicate spectra. As with the previous Allende spectra, the sample from which the finest fraction has been removed (JFB-03: 75–250 µm) is darker and bluer-sloped than the samples with the finest fraction retained (JFB-04: <150 µm). These spectra are also characterized by recognizable olivine and spinel absorption bands. The continuum-removed 1 µm region spectra of the coarsest fractions (Fig. 4r) suggest that the sample with the finest fraction removed (JFB-01) has a less well resolved olivine absorption feature in the sense that the band minimum is broader and is shifted to longer wavelengths. Band depths for each duplicate pair vary by up to 1.5% absolute for JFB-01 and 0.4% absolute for JFB-02. The 2 µm continuum-removed spectra (Fig. 4s) also show variability in band depths, again greater for JFB-01 (3.5% versus 5.5%) than for JFB-02 (2.8% versus 4.0%), but spinel-associated features are apparent in all the spectra.

For the finer-fraction spectra (Fig. 4t), the 1 µm continuum-removed spectra show less variability within each pair, with band depth varying by <0.4% absolute. The continuum-removed 2 µm region spectra (Fig. 4u) also show less variability within pairs, with band depths varying by <0.5% absolute. Band “centers” show some variability within pairs, likely due to their broad, shallow nature.

Duplicate spectra of a <150 µm fraction of Leoville were also measured with and without a black mask (Fig. 5a). The four spectra are similar in terms of overall reflectance and shape. The 1 µm region continuum-removed spectra (Fig. 5b) show absorption features near 0.95, 1.1, and 1.3 µm, whose intensity varies somewhat among the different spectra. The 0.95 µm feature may be attributable to low-calcium pyroxene, which is abundant in Leoville (Krot et al., 1998) or hydrated silicates, which are also present in Leoville (Oliver, 1978; Kracher et al., 1985). The 2 µm-region
continuum-removed spectra (Fig. 5c) are all similar, with weak absorption features in this region, but resolvable bands near 1.95 and 2.1 μm.

Reflectance spectra of a <150 μm fraction of Mokoia, measured with and without a black mask (Fig. 5d) show similar overall reflectance, although the masked spectra are more red-sloped than the unmasked sample spectra. The cause of this reddening is unknown, but we do not believe it is attributable to the mask, as this effect is not seen in other masked spectra. The 1 μm region continuum-removed spectra (Fig. 5e) show some variability in band centers, with the 1 μm region centers varying from ~1.05 to ~1.13 μm; the 1.3 μm region feature occurs near 1.33 μm. This could be due to improper removal of a continuum or mineralogical variations; the broad and shallow nature of the 1 μm region absorption feature also makes it sensitive to choice of continuum. The 2 μm region continuum-removed spectra (Fig. 5f) show weak absorption features; noise in the masked spectra makes continuum construction and band identification difficult, but the unmasked spectra exhibit the familiar spinel features near 1.95 and 2.1 μm, although a contribution by adsorbed water to the 1.95 μm feature cannot be ruled out.

The Vigarano spectra (Fig. 5g) show no appreciable difference between duplicate or between masked and unmasked spectra. The continuum-removed 1 μm region spectra (Fig. 5h) show small differences in band shapes and positions between duplicate pairs, suggesting some variability this single sample. All the spectra exhibit “olivine-like” absorption features. As with Mokoia, the masked 2 μm region continuum-removed spectra (Fig. 5i) are noisy, mak-
ing continuum construction and band identification difficult. Never-
theless, the duplicate pairs of spectra show similar absorption
bands and depths.

Duplicate spectra suggest that the CV chondrites included in
this study can be spectrally heterogeneous. However, spectral dif-
fferences for duplicate samples are generally minor, restricted to
small variations in absorption band shapes, as well as absolute
reflectance. The differences are small enough that they are unlikely
to affect meteorite comparisons with asteroids.

5.4. Grain size effects and slabs versus powders

For a number of our CV samples, we have reflectance spectra for
different grain sizes, allowing us to examine how grain size affects
CV reflectance spectra. One caveat is that some of the grain size
spectra may be for different subsamples of a particular CV, thus
there may be compositional heterogeneities between different
sample splits. A number of the CVs are breccias (e.g., Mokoia,
Vigarano), introducing the possibility of heterogeneity between
different subsamples. In addition, crushing a sample to make dif-
ferent size fractions may result in preferential depletion of
enhancement of specific phases in different size fractions, due to
differences in the strength of different phases.

5.4.1. ALH 84028

For ALH 84028, six different grain size sample spectra are avail-
able (Table 7). For the ALH 84028 for which only a maximum grain
size is specified (Fig. 6a), the spectra get progressively darker and
bluer with increasing average grain size. Reflectance in the
0.7 μm region varies from ~11% to 13.5%. The 1 μm region
continuum-removed spectra (Fig. 6b) show variations in band cen-
ters and overall absorption feature shape, suggesting that compos-
tional variations may exist between different subsamples of
this meteorite. While band position is not always within the pure
olivine field (1.045–1.085 μm), the olivine-associated inflection
near 1.3 μm is present in all of the spectra; band depths do not
vary systematically with average grain size. This could be due to
the competing effects of increasing grain size leading to lower
reflectance and deeper silicate absorption bands, at least to the
point where silicate bands become saturated, possible mineralog-
ic differences between the subsamples, and the relative impor-
tance of comminuted dark versus bright components (Johnson
and Fanale, 1973). The shorter-than expected band positions could
be associated with the presence of pyroxene (whose abundance in
this meteorite is unknown) or Fe oxyhydroxide terrestrial weather-
ing products (Schwarz and MacPherson, 1985). The 2 μm region
continuum-removed spectra (Fig. 6c) are all generally broad and
featureless, consistent with the presence of Fe2+-bearing spinels.
Band depth in this region generally increases with increasing aver-
age grain size.

The ALH 84028 spectral series with increasing average grain
size (presumably made from a single subsample of ALH 84028)
show increasingly blue slopes and decreasing overall reflectance
(Fig. 6d), consistent with the results of Johnson and Fanale
(1973) for CVs. The increasingly blue slope also shifts the 0.7 μm
local maximum to shorter wavelengths. The 1 μm continuum-re-
removed spectra (Fig. 6e) show small non-systematic differences in
band center (~1.04–1.08 μm) and the appearance of the 1.3 μm
olivine band; band depths are essentially constant for the different
size fractions. As with the continuum-removed 2 μm region

spectra of the other fractions of ALH 84028, this second series of spectra (Fig. 6f) shows little detail, and band depths increase with increasing grain size.

### 5.4.2. Allende

Allende is the most spectrally characterized CV (Table 7), with multiple grain size fractions and slab spectra. Spectra of Allende powders with no constrained minimum grain size (Fig. 7a) show no systematic variation in overall reflectance, suggestive of variations in absolute reflectance between different subsamples. The fines-free spectrum (63–125 μm) has the lowest overall reflectance and bluest spectral slope, similar in behavior to previously measured CV spectra (Johnson and Fanale, 1973). Band shapes and depths are similar for the <45, <63, <125, and <180 μm fractions in the 1 μm region, with band centers ranging between ~1.05 and 1.07 μm (Fig. 7b). The 2 μm region continuum removed spectra (Fig. 7c) all exhibit a broad shallow absorption band, but apparent band centers vary.

The Allende spectra with constrained minimum grain sizes (JFB01: 500–2000 μm; JFB3: 75–250 μm) are also blue sloped; the inclusion of the finest fraction (JFB-02: 0–200 μm; JFB-03: <150 μm) results in the appearance of an overall red slope. These four size separates of Allende exhibit variations in both overall reflectance and spectral slope (Fig. 7d).

Comparing slab spectra to a <125 μm powder made from the same slab (Fig. 7e), the slab spectra are darker and more
blue-sloped, and all show absorption features in the 1 and 2 μm region. The continuum-removed 1 μm (Fig. 7f) and 2 μm (Fig. 7g) absorption features are similar in terms of overall shape, band center, and band depth, suggesting that straight line continuum removal is effective for recovering these features in spite of variations in slope and overall reflectance, and that band depths are, unexpectedly, relatively insensitive to grain size variations.

5.4.3. Grosnaja
Spectra of four size separates of Grosnaja are shown in Fig. 8a (the <75, 75–150, and 150–500 μm spectra are from Gaffey (1974)). The spectra show no systematic variations in absolute reflectance, although the coarser samples are darker, as expected. The absorption feature in the 1 μm region (Fig. 8b), is located in the 1.0–1.05 μm interval; the <75 μm spectrum shows an additional absorption band near 0.9 μm which may be a spectral artifact. The 1.3 μm olivine absorption feature is also less apparent in the coarser grained sample spectra. The 2 μm region absorption feature is deepest in the finest fraction (<45 μm), with well-defined bands near 1.95 and 2.27 μm (Fig. 8c).

5.4.4. Vigarano
Spectra of two size fractions of Vigarano, likely from different subsamples are shown in Fig. 9a. The <150 μm fraction was measured with an integrating sphere (Gaffey, 1974), and the <100 μm fraction was measured in bidirectional mode. These spectra allow us to examine the effects of changing viewing geometry. Gradie et al. (1980), and Gradie and Veverka (1982, 1986) found that viewing geometry affects spectral slopes for Allende, and therefore comparisons of asteroid and laboratory spectra should be approached with this effect in mind. They also found that bidirectional measurements differ from integrating sphere measurements, with bidirectional spectra being generally redder than integrating sphere spectra, and the degree of difference increasing with increasing brightness. They determined that integrating sphere measurements are preferred for analysis of asteroidal spectra obtained at small phase angles. Differences in absolute reflectance on the order of 10%, relative, were found between integrating sphere and bidirectional measurements at a phase angle of 60° at 1.2 μm.

Gradie et al. (1980) and Beck et al. (2012) found that Allende shows spectral reddening, similar to other meteorites, with increasing phase angle in bidirectional measurements. French
and Veverka (1983) found that limb darkening (decrease in reflectance with increasing emission angle) was independent of wavelength over the 0.4- to 0.6-μm range. Kamei and Nakamura (2002) and Beck et al. (2012) found that reflectance of Allende powders decreases with increasing phase angle up to \( \phi \lesssim 60\)–\(90\)° and then increases toward larger phase angles.

The integrating sphere spectrum of Allende (Fig. 10a) is more red-sloped and slightly brighter than the bidirectional spectra. All three spectra show 1 and 2 μm region absorption bands. The continuum-removed 1 μm region spectrum of the integrating sphere data are noisier than the bidirectional data (Fig. 10b), “masking” the olivine signature. Band depths are generally comparable (5–6%). The 2 μm region absorption feature is broad in all the spectra (Fig. 10c), and the bidirectional data show a better resolved absorptions feature in the 2 μm region. Differences in band minima are likely attributable to the broad and shallow nature of this feature, which makes it sensitive to continuum slope.

The Leoville spectra (Fig. 10d) are similar to each other in terms of overall slope, shape, and absolute reflectance; the integrating sphere spectrum appears to be bluer sloped than the bidirectional spectra, and has an absorption feature near 0.87 μm (discussed below). As with Allende, the integrating sphere spectra are noisier. The 1 μm region continuum-removed spectra (Fig. 10e) differ between the integrating sphere and bidirectional spectra in terms of apparent absorption band positions. The bidirectional spectra have bands near 1.1 and 1.32 μm; these are at longer than

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Fig. 6. Reflectance spectra of various fractions and samples of ALH 84028 measured at RELAB. (a) Fractions with no minimum grain size or unknown grain size distribution. (b) Same as (a) for continuum-removed 1 μm region. (c) Same as (a) for continuum-removed 2 μm region. (d) Grain size series for ALH 84028. (e) Same as (d) for continuum-removed 1 μm region. (f) Same as (d) for continuum-removed 2 μm region. Linear vertical offsets applied to continuum-removed spectra are indicated in brackets on the relevant figures.
Fig. 7. Reflectance spectra of Allende. (a) Samples with unconstrained minimum grain size and 63–125 μm measured at RELAB. (b) Same as (a) for continuum-removed 1 μm region. (c) Same as (a) for continuum-removed 2 μm region. (d) Four different grain size spectra measured at PSF. (e) Slab versus <125 μm powder made from slab. (f) Same as (e) for continuum-removed 1 μm region. (g) Same as (e) for continuum-removed 2 μm region. Linear vertical offsets applied to continuum-removed spectra are indicated in brackets on the relevant figures.
expected wavelengths for olivine and likely are a function of the shallowness of this feature and the lack of a well-defined reflectance peak in the 1.5 μm region for fixing a continuum. In the 2 μm region (Fig. 10f), the integrating sphere spectrum has a shallower absorption feature with no well-defined absorption bands, while the bidirectional spectra are deeper and display absorption bands near 1.95 and 2.1 μm, as seen in other CV spectra, such as Allende. There are also indications of an additional feature near 2.3 μm, which may be attributable to hydrous phases which are present in Leoville (Oliver, 1978; Kracher et al., 1985).

The integrating sphere spectrum of Mokoia is brighter and redder in the visible region, and shows more “spectral features” than the bidirectional spectra (Fig. 10g). These include the 0.87 and 1.37 μm features discussed below. As with some of the other spectra discussed above, the positions of the “olivine bands” differ (Fig. 10h): ~1.05 and 1.25 μm for the integrating sphere versus ~1.11 and 1.32–1.35 μm for the bidirectional spectra. Once again, some of these variations are probably related to their sensitivity to small differences in the continuum, and the wavelength offset of the spectrometer used to collect the Gaffey (1974) data (McFadden et al., 1982); however band depths are comparable for all three spectra. Similar to some of the previous CV spectra, the bidirectional spectra show better resolved 1.95 and 2.1 μm bands, as well as a possible 2.3 μm feature (Fig. 10i), but the 2 μm region absorption feature is shallow (~<4% depth) and wide.
For Vigarano (Fig. 10j), the integrating sphere spectrum is brighter and less blue-sloped (redder) than the bidirectional spectra, with peak reflectance of 8% versus 5.5%. All the spectra exhibit broad 1 and 2 μm region absorption features. The continuum-removed 1 μm region (Fig. 10k) show deeper 1.1 and 1.3 μm absorption features for the bidirectional spectra. As with Mokoia, these two absorption bands are at longer than expected wavelengths for olivine; this could be attributable to a number of causes, such as amorphous Fe-bearing material, phyllosilicates, or magnetite. Uncertainty in continuum position seems unlikely, as the Vigarano spectra have a well-defined local reflectance maximum in the 1.5 μm region. The 2 μm region (Fig. 10l) shows deeper overall absorption and better-resolved absorption bands near 1.95 and 2.1 μm in the bidirectional spectra.

The 0.87 and 1.37 μm features are seen in all the integrating sphere spectra. It seems likely that these are artifacts whose cause is unknown. The 0.87 μm feature could plausibly be assigned to Fe oxyhydroxides, but the expected UV–visible reflectance edge is not present; the 1.37 μm feature occurs at longer wavelengths than expected for olivine and shorter wavelengths than expected for OH/H2O. The differences in band positions between some of the integrating sphere and bidirectional spectra could be due to a wavelength offset that was recognized well after the Gaffey (1974) data were acquired (McFadden et al., 1982). The Gaffey (1974) data have not been corrected for this offset, as its magnitude is likely wavelength dependent and may have varied over time. The better resolved nature of the absorption bands in the bidirectional data, particularly in the 2 μm region is likely attributable to the higher

Fig. 10. Integrating sphere (Gaffey, 1974) versus bidirectional (i = 30°; e = 0°) PSF reflectance spectra of <150 μm CVs and continuum-removed 1 and 2 μm regions, respectively, for: (a–c) Allende; (d–f) Leoville; (g–i) Mokoia; (j–l) Vigarano. Linear vertical offsets applied to continuum-removed spectra are indicated in brackets on the relevant figures.
signal to noise of the bidirectional data, as spectral resolution for the Gaffey (1974) and RELAB data are comparable (5 nm).

The lack of systematic reddening or bluing between integrating sphere and bidirectional measurements is likely due to the “natural” spectral variability that seems to characterize some CVs. Duplicate measurements of various CVs, discussed above, can show changes in overall slope and absolute reflectance. This can likely be attributed to differences in surface texture, and the relative abundances of different minerals and grain size distribution in the uppermost surface of the sample when the samples are emptied and repacked for duplicate spectral measurements. These differences appear to become more apparent in the larger grain size fractions.

The integrating sphere measurements show what are likely some spurious absorption features. Nevertheless, it appears that they type of spectral measurement (integrating sphere, bidirectional) does not negatively impact our ability to characterize CVs on the basis of their diagnostic absorption features, particularly Fe-rich olivine features in the 1 μm region and Fe²⁺-bearing spinel features in the 2 μm region.

5.6. CAIs, AOIs

The reflectance spectrum of the unsorted powder (~1 g) of a mixture of two large CAIs from Allende (made by extracting the CAIs using a rotary tool) are much brighter than a bulk Allende
powder (Fig. 11a), and absorption features in the 1 and 2 \( \mu m \) region are apparent. The continuum-removed 1 \( \mu m \) region spectrum of the CAI powder consists of a broad region of absorption from \( \approx 0.6 \) to \( \approx 1.4 \mu m \), with suggestions of contributions from a number of absorption bands; the bulk Allende spectrum, by contrast is dominated by olivine (Fig. 11b). The 1 \( \mu m \) region CAI spectrum is most consistent with spectral contributions from fassaite, which has bands near 0.75, 0.95, and 1.15 \( \mu m \) (Fig. 1b). The 2 \( \mu m \) region shows how much deeper absorption in this region is for a CAI concentrate compared to bulk Allende (Fig. 11c). The CAI spectrum shows indications of absorption bands near 1.95 and 2.1 \( \mu m \), but these are better expressed in bulk CV spectra, and are most consistent with major spectral contributions from Fe\(^{2+}\)-bearing spinel (Fig. 1b). Fassaite does not seem to contribute significantly to the 2 \( \mu m \) region of CAI spectra.

Rajan and Gaffey (1984) measured reflectance spectra of various high-albedo inclusions in a slab of Allende and found diverse spectral behavior that could be related to mineralogy. Some were dominated by spinel, others showed spectral contribution from fassaite and augite (0.9–1.1 and 2.4 \( \mu m \)). In a more detailed study of Allende inclusions by Sunshine et al. (2008a,b), fluffy type A inclusions were found to have the most intense 2 \( \mu m \) region absorption feature, AOIs were spectrally dominated by olivine, and type B CAIs, which contain fassaite, were red-sloped and had a shallower 2 \( \mu m \) region absorption feature.
5.7. Dark inclusions

Dark inclusions are common at the few% level in a number of CVs. Buchanan et al. (2010) noted that a type B dark inclusion from Allende, dominated by fine-grained olivine, had an absorption band near 1.05 μm, and its spectrum was different from that of bulk Allende, although no details were provided. Fig. 12a shows reflectance spectra of bulk NWA 3118 and a dark inclusion from it. The two spectra (both <125 μm) have similar overall reflectance, and the dark inclusion has a redder slope and less well-defined 1 μm region absorption band. The continuum-removed 1 μm regions (Fig. 12b) have similar band positions and shapes, and band depth is slightly less in the dark inclusion spectrum. The 2 μm region continuum-removed spectra (Fig. 12c) both exhibit an absorption feature in this region, with the dark inclusion band being shallower, and having its minimum at a longer wavelength. These results suggest that comminution of a CV largely eliminates any differences in overall reflectance that may exist between dark inclusions and a bulk CV, but that the CAI/spinel contents of a bulk CV and dark inclusions do differ (Fruland et al., 1978).

5.8. Thermal metamorphism and melting

Reflectance spectra of Allende (<63 μm grain size) heated to various temperatures (Miyamoto et al., 2000) are shown in Fig. 13a and b. The sample was ground to <100 μm, heated to various temperatures with an oxygen fugacity of IW − 1, and then reground and resieved prior to the spectral measurements. Absolute reflectance in the 0.7 μm region varies non-systematically between ~8% and 11% up to ~900 °C. Above this temperature, absolute
reflectance increases, particularly above 1000 °C. The spectra also become more “olivine-like” with an increasingly prominent 1 µm region absorption band. This is seen more clearly in the continuum-removed spectra (Fig. 3c and d), particularly above ~1000 °C where band depth starts to increase. The 2 µm region shows similar behavior (Fig. 3e and f); band depth does not begin to increase until ~1100 °C, and above this temperature, a spinel-like absorption feature becomes very prominent and deep.

Miyamoto et al. (2000) heated samples of Allende to 800 °C at oxygen fugacities of IW + 2 and IW – 1. The IW + 2 spectrum was brighter than the starting sample, with the same overall slope, a more gradual reflectance rise in the visible region, and still displayed a resolvable olivine absorption band. The IW – 1 spectrum was also brighter than the starting material but more red-sloped and with a shallower olivine absorption band. These results suggest that thermal metamorphism at these temperatures and associated oxygen fugacity can affect CV spectra. The change in slope and overall reflectance is not seen in the Allende spectra heated to 800 °C shown in Fig. 13, suggesting that spectral changes in CV are sensitive to specific experimental conditions.

King et al. (1983) used a solar furnace to melt samples of Allende at temperatures of ~3000 °C in vacuum (King, 1982). The resulting condensates ranged from red-sloped and featureless to similar to the starting material. The spectral differences were attributed to variations in the experimental conditions with preferential loss or retention of different elements (King, 1982).

6. Discussion

The development of spectral–compositional correlations for CVs is hampered by a number of factors: the small number of CVs that have been spectrally characterized and that they are distributed across different subgroups (CV6, CV7, CV8); the low level of agreement concerning petrologic subtype assignments; the lack of detailed mineralogy/petrology for a number of the CVs included in this study; and the brecciated nature of some CVs. As a result, we can make no more than some tentative observations concerning CV spectral properties.

Considering the oxidized versus reduced subgroups, the major differences that may impact their reflectance spectra are the slightly higher metal: magnetite ratios in CV6 versus CV7 chondrites, and the fact that CV7 chondrites may contain a few wt.% phyllosilicates. We might expect the former to result in redder slopes for CV7 versus CV6. However, the CV7 spectra are not red-sloped compared to the CV6 spectra, probably because metal and magnetite abundances are too low to appreciably affect overall slopes. Similarly, phyllosilicate abundances in the CV6 chondrites appear to be too low to result in expected phyllosilicate absorption bands near 0.7 and 1.1 µm as are seen in CM spectra (Cloutis et al., 2011a). The spectral properties of CV carbonaceous phases are not well known. Only a carbonaceous extract of Allende has been measured (Johnson and Fanale, 1973); it is dark (<4% reflectance) and blue-sloped.

With increasing metamorphism, we might expect changes in factors such as overall reflectance and mafic silicate absorption band depth, largely due to the loss and aggregation of carbonaceous phases. This is clearly seen in the heated Allende spectra. When we examine the CV spectra as a function of metamorphic grade, even accounting for differences in assignments between Guimon et al. (1995) and Bonal et al. (2006), we find that overall reflectance and absorption band depths are not correlated with metamorphic grade. This is likely attributable to the small sample size and limited range of petrologic subtypes that are available.

When we examine the absorption feature in the 1 µm region, we find that its overall shape is most consistent with olivine. For Allende, band centers, regardless of grain size, are confined to the 1.05–1.08 µm region, within the range for pure olivine. For some of the other CV spectra, band “center” can range from ~1.0 to ~1.13 µm. We believe there are two reasons for these wider ranging values: many of the CV spectra have shallow and broad absorptions in this wavelength region, and many have poorly defined local reflectance maxima in the 1.5 µm region. As a result, small variations in the slope of the continuum used to isolate these bands can have a measurable effect on band positions.

Interestingly, a very pervasive feature in the CV spectra is an absorption feature near 1.3 µm. This is attributable to olivine, and its appearance in so many CV spectra is attributable to the fact that much of the matrix olivine in CVs is Fe-rich, and with increasing Fe, this band becomes more prominent relative to the 1.05 µm center olivine band (King and Ridley, 1987).

The 2 µm region of CVs is characterized by a nearly ubiquitous absorption feature which is most consistent with Fe²⁺-bearing spinels (Cloutis et al., 2004). It commonly exhibits band minima/centers near 1.95 and 2.1 µm. Differences in band positions for some CVs is again due to the broad and shallow nature of this feature, making it very sensitive to choice of continuum. Nevertheless, it appears that a spinel-associated absorption feature is characteristic of CVs regardless of their petrologic subtype, although it should be noted that the low petrologic grade CVs, Leoville and Vigarano have among the shallowest bands in this region; we believe that it is due to their low petrologic subtype rather than the fact that they are CV6 chondrites. Band depths in this region are not consistently higher in CV6A spectra in spite of the fact that alteration of these meteorites leads to entry of Fe into CAI spinels (Krot et al., 1995).

The heating experiments on Allende show that the 2 µm region absorption feature deepens when temperature exceeds ~1000 °C.

Band area ratio, which has been found to be a useful criterion for characterizing olivine + low calcium pyroxene mixtures (Cloutis et al., 1986) was examined for its utility in characterizing CV chondrites. Band area ratios are zero for pure olivine and the II/A/I ratio range up to ~0.9–1.1 for pure pyroxenes (Cloutis et al., 1986). The II/I area ratio ranges up to ~3.5 for pure low calcium pyroxenes (Cloutis and Gaffey, 1991). The II/A/I and II/I band area ratio values for the powdered CAIs from Allende are 6.4 and 6.8, respectively, well above the range for even pure orthopyroxene. This arises from the fact that their spectra are dominated by spinel which has a strong 2 µm region band and no 1 µm region band. However, most of the CV spectra band area ratios fall in the orthopyroxene to olivine range, suggesting that band area ratios are not useful for recognizing CAIs/spinels on their own. The presence of spinels rather than orthopyroxene is best achieved by: (1) using the fact that spinel band minima are located near 2.1 µm region, while orthopyroxene band minima occur at shorter wavelengths (1.85–2.1 µm) (Cloutis and Gaffey, 1991); orthopyroxene-influenced spectra would exhibit their band 1 centers below 1.05 µm (Cloutis et al., 1986), whereas spinel-influenced spectra have no effect on band 1 position; (2) the 2 µm region absorption feature is broader than the orthopyroxene feature, and hence does not show a large upturn in reflectance longward of ~2.1 µm.

Grain size variations have measurable effects on CV spectra. Johnson and Fanale (1973) first demonstrated that CV and other CCs become darker and bluer with increasing average grain size, and our measurements on slabs versus powders for Allende confirm this, but this trend is not seen in all CV spectra. We have also found that increasing average grain size and removal of the finest fraction both lead to increasingly blue overall slopes. We have also found that straight line continuum removal in the 1 µm region can successfully and repeatedly recover band centers in the 1 and 2 µm regions.

The heating experiments on Allende suggest that CVs that are thermally metamorphosed will display more prominent olivine
and spinel features. This can be attributed to the loss/aggregation of carbonaceous phases, and possibly devitrification/crystallization (as olivine) of any amorphous or poorly crystalline phases that may be present; such material has been found in ALH 84002 (Schwarz and MacPherson, 1985). The heating experiments on Allende suggest that measurable spectral changes of this sort require temperatures on the order of 1000 °C. When CVs are exposed to melting temperatures (King et al., 1983), the resulting condensates can be very spectrally variable, resembling the starting material, or being strongly red-sloped and spectrally featureless.

CV spectra measured in bidirectional mode versus with an integrating sphere suggest that integrating sphere measurements can be similar to, or different from, bidirectional measurements in terms of overall reflectance and spectral slope. Some of this variation is likely attributable to differences in the uppermost surfaces of the samples between sample packing. Detailed measurements (Gradie et al., 1980; Gradie and Veverka, 1982) suggest that bidirectional measurements on Allende are redder than integrating sphere measurements. These differences are accentuated as phase angle increases – Allende spectra become increasingly red with increasing phase angle (Beck et al., 2012).

The CV falls and finds show a possible difference in visible region slopes, with the falls being less red-sloped than the finds. This is the same behavior seen in ordinary chondrites (Salisbury and Hunt, 1974), and suggests that falls should be preferred when conducting spectroscopy-based searches for CV parent bodies, particularly when the visible region is used in such a search.

6.1. CV versus CK chondrites

Possible links between CK and CV3OxA chondrites have been suggested by a number of investigators. Greenwood et al. (2003, 2004) suggested that the mineralogic and petrologic differences that exist between CV and CK chondrites reflect higher metamorphic grades in CKs and that CKs are a metamorphic extension of CVs. Mineralogic differences that may be consistent with thermal metamorphism of CVs to form CKs include low chondrule to matrix ratio, low abundance of refractory inclusions, low C content, and magnetite compositional differences (Greenwood et al., 2003, 2004). A tentative CK4 chondrite, TNZ 057, was found to contain abundant dark inclusions and CAIs similar to those found in CVs (Devouard et al., 2006). NWA 1628, also initially classified as a CK4 chondrite, has matrix olivine composition similar to CV3OxA chondrites, but its matrix is coarser (Brearley, 2009). A comparison of CV3OxA chondrites to CK3 and CK4 chondrites but Chaumard et al. (2009) also suggests that various mineralogic and petrologic differences that are seen are consistent with these meteorites representing a continuous metamorphic sequence. These differences include (with increasing metamorphism) higher matrix abundance, lower chondrule abundance, and enrichment of Fe in CAIs (Chaumard et al., 2009).

How and whether similarities and differences between these two classes would be expressed spectroscopically is not fully constrained. CVs differ from CKs in terms of the former having a lower average abundance of matrix (49–67% versus 66–75%), higher abundance of chondrules (22–41% versus 18–27%), and higher abundance of CAIs (9.9–11.4% versus 2.1–12.5%) (Chaumard et al., 2009). Olivine compositions are largely similar between CVs and CKs (Brearley and Jones, 1998), and given that olivine absorption bands shift only marginally (by ~0.040 μm) from Fa0 to Fa100 (King and Ridley, 1987), we would not expect to find measurable differences in 1 μm region band centers between CV and CK spectra. The apparent lower abundance of CAIs in CKs could result in weaker CAI-associated absorption bands in the 2 μm region, however, with increasing metamorphism, fine-grained CAIs become enriched in Fe, and if this Fe is ferrous and enters spinels, their absorption bands become stronger (Cloutis et al., 2004).

With increasing metamorphism we would expect carbonaceous opaques to aggregate and possibly volatilize. This would result in higher overall reflectance for CKs and deeper olivine and spinel absorption bands with increasing metamorphism, which could be a potentially useful spectral parameter to distinguish CVs from metamorphosed CKs.

A cursory comparison of Allende (CV ~ 3.7), heated Allende, and some CK3 and CK4 chondrites (Fig. 14a), shows that unheated Allende has the lowest overall reflectance, which increases upon heating above ~1000 °C; its reflectance is also lower than the overall reflectance of the CK3 and CK4 chondrites of comparable grain size. This strongly suggests that thermal metamorphism does lead to an increase in overall reflectance. Increasing temperature of heating of Allende also leads to an increase in 2 μm region spinel absorption band depth. The least metamorphosed CK, MET01149 (CK3; McBride et al., 2003), does show an absorption feature in this region, of comparable depth to unheated Allende (Fig. 14b). The more metamorphosed CKs, ALH 85002 (CK4; Score and Lindstrom, 1994) and DAV 92300 (CK4; Score and Lindstrom, 1993) have shallower 2 μm region absorption features than unheated Allende, heated Allende, and MET 01149. This suggests that while Fe may enter CAIs as a result of thermal metamorphism, it may not be incorporated into spinels, and/or the lower CAI content in CKs may counteract any increase in spinel Fe content. A detailed comparison of CV and CK chondrites will be included in a subsequent paper in this series.

Fig. 14. (a) RELAB reflectance spectra of Allende (unheated, 1100 °C, and 1200 °C), and some CK3 and CK4 chondrites. (b) Same as (a) for the 2 μm region; some spectra have been offset for clarity.
6.2. CV versus CO chondrites

Compositionally, CO and CV chondrites are quite similar (e.g., Brearley and Jones, 1998). Petrologic parameters that are used to distinguish members of these two groups, such as chondrule size, texture, and matrix abundance (e.g., Dodd, 1981), would probably not be useful in analysis of telescopic spectra for possible CO and CV parent bodies, as large asteroid surfaces are generally fine-grained (e.g., Dollfus, 1971; Dollfus et al., 1975; Helfenstein et al., 1994; Veverka et al., 2000), and hence chondrules and other meteorite components would be comminuted and homogenized. As an example, one of the criteria that has been adopted for discriminating COs from CVs is abundance of matrix (average of 42 vol.% in CVs versus average of 34 vol.% in COs (Dodd, 1981)). Other spectral parameters that could lead to measurable spectral differences, such as olivine Fe<sup>2+</sup> content or CAI abundances, are similar enough (Table 1; Brearley and Jones, 1998) to suggest that these two groups would, on average, be spectrally indistinguishable, particularly as both groups include members of varying petrographic subgrades (e.g., Scott and Jones, 1990; Bonal et al., 2006).

Spectral differences between some COs and CVs with similar overall reflectance and slopes are shown in Fig. 15a. Superficially there is little to distinguish them. When the 1 μm region is examined in detail (Fig. 15b), Y-86751, has a more pronounced 1.3 μm olivine absorption band, but the other CV, ALH 84028, does not. The 2 μm region of these spectra (Fig. 15c) also shows no major spectral differences that can reliably be applied to distinguish CO from CV spectra; all four spectra exhibit a spinel-associated absorption feature in this region. The small differences in overall slope exhibit overlap between CO and CV spectra. A detailed comparison of CO and CV spectra will be the subject of a future paper.

6.3. CV parent bodies

CV parent bodies among main belt asteroids have been tentatively identified using spectroscopic data. Burbine et al. (2001) found that the 0.4–1.6 μm spectrum of the Eos family asteroid 599 Luisa was well matched in the UV and presence of an absorption band near 1.1 μm by Mokoia and Allende. However, as discussed above, spectral parameters that are used for matching asteroid and meteorite spectra may not provide as much specificity as would be desired. For example, overall spectral slopes and reflectance of CVs, and other CCs, can vary within a single meteorite, as a function of phase angle, and with changes in grain size. Slopes in the visible region also seem to differ between CV falls and finds, with falls having less-red slopes. Thus spectral matching should be undertaken using falls when possible.

As discussed above, we have found that CV spectra may be largely indistinguishable from CO spectra. The most useful differences are a generally well-defined 1.3 μm olivine absorption band in CV spectra, generally stronger than the same band in CO spectra, spinel absorption bands near 1.95 and 2.1 μm, also generally better defined in CV spectra, and a 1 μm region absorption band in the 1.05–1.08 μm region in most CV spectra, whereas the same band is often shifted to >1.1 μm in CO spectra.

Our analysis suggests that the mineralogic and petrologic differences that exist between the CV<sub>ox</sub> and CV<sub>K</sub> Classes, and the varying petrologic subtype included in our sample suite (CV3.0→3.7), are not significant enough to result in measurable spectral differences that exceed spectral variations within a subgroup, within an individual meteorite, or as a function of grain size. Similarly, CO and CV chondrites are spectrally quite similar, which is not surprising given their similar mineralogies. Terrestrial weathering also seems to affect CV spectra, most noticeably in the visible region, resulting in more red-sloped spectra for finds as compared to falls, further obscuring spectral–compositional trends using this wavelength region.

The search for CV parent bodies should focus on the detection of olivine and spinel absorption bands, specifically absorption features near 1.05, 1.3, 1.95, and 2.1 μm, as these are the most commonly seen spectral features of CV chondrites. As mentioned, an astronomer searching for a CV parent body would likely not be able to differentiate a CO from a CV parent body (as discussed earlier). We would want to match spectra to CV falls where possible, and should be careful to take into account grain size and viewing geometry. Particular emphasis should be placed on characterizing diagnostic absorption features in the 1 and 2 μm region, over other spectral characteristics such as absolute reflectance, overall spectral shape, or slope. Any CV parent body can reasonably be expected to have absorptions at or near 1.05, 1.3, 1.95, and 2.1 μm.

![Fig. 15.](attachment:image)

(a) RELAB reflectance spectra of some CO and CV chondrites that have superficial similarities. (b and c) Same as (a) for the 1 and 2 μm regions, respectively; some spectra have been offset for clarity.
While not pursued here, there are a number of lines of evidence, including paleomagnetic studies of CVs (e.g., Elkins-Tanton et al., 2011; Carporzen et al., 2011; Humayun and Weiss, 2011), and various isotopic data (Clayton and Mayeda, 1996) that link CVs to partially differentiated bodies. Tentative links between CVs and the Eagle Station pallasite grouplet have been made on the basis of these various lines of evidence (e.g., Humayun and Weiss, 2011). Preliminary thermal models suggest that temperatures in the interior of a 50 km diameter CV parent body could have reached 1000 K (Wakita et al., 2011).

7. Summary and conclusions

CV chondrites, as with most other CC groups, exhibit spectral differences that can be attributed to factors such as grain size, redox conditions, and degree and duration of thermal metamorphism. The most ubiquitous absorption features associated with CV spectra are broad regions of absorption in the 1 and 2 μm region. The 1 μm region feature is usually centered near 1.05–1.08 μm with an additional band near 1.3 μm. These two features are attributable to Fe-rich olivine. Absorption in the 2 μm region usually shows two minima near 1.95 and 2.1 μm that are attributable to Fe²⁺-bearing spinel.

As with other CC groups, CV spectra are diverse, with differences in overall reflectance, slope, and intensity of absorption bands. This complicates the derivation of spectral parameters that can be used to recognize CV subgroups (CV₆ₓ, CVₓₙ₋ₓ, CVₓₒₓ), petrologic subtypes, or even to reliably discriminate CVs from other carbonaceous chondrites. In common with some other CCs, it appears that the least metamorphosed members exhibit the most weakly featured reflectance spectra. Also in common with other CCs, finely-dispersed opaque components have a large influence on CC spectra by reducing overall reflectance, reducing mineral absorption band depths, and imparting red or blue slopes to the spectra.

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Appendix A. Composition of individual CVs included in this study

A.1. ALHA 81003 (CV3.0–3.1)

ALHA 81003 contains abundant irregular shaped white inclusions on a black surface, and the presence of metal was noted (Score and Mason, 1983). It contains numerous chondrules and irregular crystalline aggregates in a minor amount of dark brown to back semi-opaque matrix (Score and Mason, 1983). Tonui et al. (2002) describe it as consisting of low-Ca-richtyroxene-rich chondrules and fayalite olivine-rich matrix (Tonui et al., 2002). The chondrules and aggregates consist mostly of olivine with a wide compositional range (Fa₀₋₄₀, mean Fa₁₈) (Score and Mason, 1983). Trace amounts of Fe–Ni-metal are present as minute grains, and finely dispersed sulfide is present in minor amounts (Score and Mason, 1983). The matrix consists largely of fine-grained iron-rich (Fa₄₀₋₆₀) olivine (Score and Mason, 1983). The olivine is compositionally heterogeneous (Fa₄₀₋₆₀), while the pyroxene is uniform in composition (Fs₁) (Score and Mason, 1983). It contains 0.8 wt.% C and 1.5 wt.% S (Gibson and Andrews, 1980). The chondrules show evidence of metasomatism, and the high degree of homogeneity of the matrix olivines is evidence of thermal metamorphism (Tonui et al., 2002). It shows mobile trace element evidence of thermal metamorphism (Wang and Lipschutz, 1998; Lipschutz et al., 1999).

A.2. ALH 84028 (CV3.2 – oxidized A subgroup)

The interior is gray with numerous lighter inclusions and a few oxidation haloes (Schwarz and MacPherson, 1985). In thin section, a variety of chondrules, clasts, and inclusions are distributed in a pristine matrix consisting of (at least) olivine (Fa₄₅₋₅₀), troilite, and awaruite (Schwarz and MacPherson, 1985). The matrix consists largely of olivine, with disseminated sulfides (Abreu and Brearley, 2003). Matrix olivine is Fa₁₂₋₂₅, average Fa₂₂₋₂₅, comparable to Allende (Abreu and Brearley, 2003). Many chondrules contain devitrified glass; olivine in chondrules and larger matrix grains range from Fa₀ to Fa₃₀, with most Fa₀₋₁₀ pyroxene grains are mostly close to Fs₂₅₋₃₀; refractory inclusions are also present (Schwarz and MacPherson, 1985). Chondrule edges show evidence of secondary fayalitic olivines, and metal and metal sulfides show evidence of extensive alteration, typical of CV3 chondrites (Abreu and Brearley, 2003). Sulfides and oxides are the most common inclusions in olivine. The olivines in ALH 84028 and Allende may have formed by thermal metamorphism of preexisting phyllosilicates (Abreu and Brearley, 2003). No magnetite was detected by Mössbauer analysis, consistent with <0.5 wt.% magnetite (Bland et al., 2000). It contains 0.12 wt.% C (Alexander et al., 2007).

A.3. ALH 85006 (CV3 – oxidized subgroup)

The interior is made up of chondrules and white inclusions (Martinez and Mason, 1986). In thin section, chondrules, chondrule fragments, and irregular clasts are set in a dark brown to black matrix (Martinez and Mason, 1986). It contains fine-grained opaques dispersed in the matrix and rimming some of the chondrules (Martinez and Mason, 1986). The matrix consists largely of fine-grained iron-rich olivine (Fa₄₅₋₄₇). Olivine in the chondrules and mineral fragments is near Fa₀, and more iron-rich olivine is also present (Martinez and Mason, 1986). Pyroxene is much less abundant and close to Fs₀ (Martinez and Mason, 1986). Gooding (1986) notes that both the olivine (Fa₀₋₃₋₄₃) and pyroxene (Fs₁₋₅) are compositionally heterogeneous in this meteorite. It contains 8 wt.% magnetite (Bland et al., 2000) and is a member of the oxidized group (Hoffman et al., 2000).

A.4. Allende (CV3.2–3.3 – oxidized A subgroup)

Allende is the most-studied CV chondrite. It contains 38.4 vol.% matrix and 0.18 wt.% C (Alexander et al., 2007). McSween (1977) gives a composition of: 43 vol.% chondrules, 3.2 vol.% AOIs, 9.4 vol.% CAIs, 2.9 vol.% lithic and mineral fragments, 38.4 vol.% matrix, 0.2 vol.% metal, 1.7 vol.% sulfides, and 1.2 vol.% magnetite, by optical point counting. Modal mineralogy for Allende includes <0.3 vol.% (<0.5 wt.% magnetite (Bland et al., 2000, 2004). Refractory inclusions are present at ~5 wt.% (Grossman, 1980). Average areal abundance of CAIs is 5.02% (Hezel et al., 2008). Submicron chromite is common along healed cracks and grain boundaries in chondrule olivine (Housley, 1981). Fayalitic-rich rims, veins and
halos appear to be common in forsteritic olivine in chondrules, CAIs, and single grains (Peck and Wood, 1987; Hua et al., 1988). Matrix olivine compositions are centered around Fa$_{27}$ (Peck, 1983). Mössbauer analysis indicates a prevalence of Fe$^{2+}$-bearing olivine, a small amount of either goethite or phyllosilicates, and no evidence of ferromagnetic minerals, such as iron oxides, magnetite, metallic Fe and troilite (Oliver et al., 1984). Mössbauer spectroscopy suggests that olivine and phyllosilicates (Fe$^{3+}$-bearing) are present; Fe$^{3+}$/total Fe = ~10% (Fishers and Burns, 1991). Natural remnant magnetization suggests the presence of pyrrhotite, taneite, and magnetite (Nagata et al., 1991). Chondrule olivine composition is narrow (Fa$_{14}$) (Simon and Haggerty, 1980). Olivine and pyroxene compositions average Fa$_{10}$ and Fs$_{4.1}$, respectively (McSween, 1977). Matrix phyllosilicate Fe/(Fe + Mg) ranges from 45 to 55 (Zolensky et al., 1993). Matrix and chondrule rims average Fe/(Fe + Mg) of 0.50 and 0.50, and wt.% S of 0.45 and 0.41, respectively (Zolensky et al., 1993).

Dark inclusions are common in Allende than in other CV3 chondrites (Kojima and Tomeoka, 1996). Dark inclusions range from ones composed of chondrules and CAIs embedded in a fine-grained matrix resembling host CV3 meteorites, to fine-grained homogeneous Fe-rich olivine (Fa$_{25-33}$) (Kojima and Tomeoka, 1996). Dark inclusions may have suffered aqueous alteration followed by thermal metamorphism (Kojima and Tomeoka, 1996).

Bulk C content is 0.27 wt.% (Pearson et al., 2006), 0.29 wt.% (Jarosewich, 1996), or 0.37 wt.% (Halbout et al., 1986). Carbonaceous matter is concentrated on olivine surfaces, particularly in the dark halos surrounding some chondrules and aggregates (Bunch and Chang, 1980). Allende’s magnetic properties have led to the suggestion that it may have come from a partially differentiated CV parent body, possibly linked to the Eagle Station pallasite, which would represent a sample of the core-mantle boundary (Weiss et al., 2010).

A.5. Grosnaja (CV3.2–3.3 – oxidized B subgroup)

It contains 36 vol.% chondrules, 3.3 vol.% AOs, 2.8 vol.% CAIs, 2.3 vol.% lithic and mineral fragments, 51.3 vol.% matrix, a trace amount of metal, 2.9 vol.% sulfides, and 1.4 vol.% magnetite, by optical point counting (McSween, 1977). Olivine and pyroxene compositions average Fa$_{11}$ and Fs$_{4.4}$, respectively (McSween, 1977). Matrix olivine compositions are fairly homogenous and cluster around Fa$_{10}$ (Van Schmus, 1969). Microprobe traverses show that the bulk of the olivines are Fa$_{20}$, and the rarer pyroxenes are generally Fs$_{5}$ (Wood, 1967a). Mason (1963) found that olivine composition ranges from Fa$_{9}$ to Fa$_{99}$. It contains 2.6 wt.% magnetite (Bland et al., 2000), and no metal (Wood, 1967b). It has undergone aqueous alteration, resulting in the formation of phyllosilicates in the matrix and chondrules. Serpentinite is the most abundant matrix phyllosilicate, mixed with a chlorite group mineral and rare smectite (Keller and McKay, 1993). The phyllosilicates occur with Mg-rich carbonates, fine-grained magnetite, chromite and pentlandite and poorly crystalline FeNi-oxide/hydroxide. The serpentines are Fe-rich (Fe/(Fe + Mg) = -0.5) (Keller and McKay, 1993). Chondrule mesostasis is altered to Na-saponite (Fe/(Fe + Mg) = 0.1) (Keller and McKay, 1993). Bulk C content is 0.71 wt.% (Pearson et al., 2006). The matrix contains 0.6 wt.% C, and 26% Fe (Wood, 1967b).

A.6. Leoville (CV3.0 – reduced subgroup)

McSween (1977) describes Leoville as containing 51.4 vol.% chondrules, 1.3 vol.% AOs, 6.6 vol.% CAIs, 1.1 vol.% lithic and mineral fragments, 35.1 vol.% matrix, 1.8 vol.% metal, 2.1 vol.% sulfides, and 0.6 vol.% magnetite, by optical point counting. May et al. (1999) found 1.89% CAIs by area. Leoville contains 35.1 vol.% matrix (Alexander et al., 2007). The matrix is dominated by fine-grained (typically <1 μm) fayalitic (Fa$_{80-60}$) olivine; low-Ca pyroxene is abundant; metal is present and phyllosilicates are absent (Krot et al., 1998). Olivine and pyroxene compositions average Fa$_{6.4}$ and Fs$_{5.8}$, respectively (McSween, 1977). It is less metamorphosed than Allende; olivine composition is Fa$_{90-70}$, with most Fa$_{10}$, especially in the chondrules; pyroxene is almost uniformly Fs$_{16}$ (Kracher et al., 1985). It shows a preferred textural orientation, possibly due to shock compression (Muller and Wlotzka, 1982). Numerous dark inclusions include xenolithic CM-type materials, while others are similar to the host matrix (Kracher et al., 1985). All components of Leoville have undergone hydrous alteration to varying degrees (Kracher et al., 1985). Mössbauer analysis indicates the presence of hydrated and anhydrous silicates, magnetite, troilite, and Fe–Ni metal (Oliver, 1978). It contains 3.8 wt.% magnetite according to Bland et al. (2000), although Krot et al. (1998) found no magnetite. Bulk C content is given as 1.14 wt.% (Pearson et al., 2006) or 0.61 wt.% (Alexander et al., 2007).

A.7. Mokoia (CV3.0–3.2 – oxidized B subgroup)

It contains 46.9 vol.% chondrules, 2.7 vol.% AOs, 3.5 vol.% CAIs, 3.6 vol.% lithic and mineral fragments, 39.8 vol.% matrix, a trace amount of metal, 1.6 vol.% sulfides, and 1.9 vol.% magnetite, by optical point counting (McSween, 1977). It contains 39.8 vol.% matrix according to Alexander et al. (2007). It appears to consist of different oxidized and reduced CV3 lithologies (Krot et al., 1998). Of the objects >100 μm in diameter in Mokoia, 13 vol.% are various types of inclusions (CAIs: 6.5 vol.%; AOs: 6.5 vol.%) (Cohen et al., 1983). May et al. (1999) found 0.65% CAIs by area. The matrix is dominated by fayalitic olivine (Fa$_{20-40}$) (Krot et al., 1998); some olivine has been replaced by a mixture of smectite (saponite) and Fe oxide (Keller and Buseck, 1990a).

Olivine compositions range from almost pure forsterite to almost pure fayalite (Hua and Buseck, 1995). The bulk of the olivine in chondrules is Fa$_{3.5}$ (Cohen et al., 1983). Chondrule olivines cluster around Fa$_{12}$ (Van Schmus, 1969). Microprobe traverses show that the bulk of the olivines are Fa$_{10}$, and the rarer pyroxenes are generally Fs$_{4.5}$ (Wood, 1967a). Olivine composition ranges from Fa$_{9}$ to Fa$_{99}$ (Mason, 1963). The presence of Fa$_{0}$ olivine was identified by X-ray diffraction analysis (Bass, 1971). Olivine and pyroxene compositions average Fa$_{11.7}$ and Fs$_{4.1}$, respectively, according to McSween (1977).

It contains sparse phyllosilicates that are largely Fe-bearing saponite in the matrix, and Fe-bearing saponite (2–4 wt. %FeO) and Na-rich phlogopite in the chondrules, aggregates, and inclusions (Tomeoka and Buseck, 1990). The saponite resulted from hydration of Fe-rich olivines, with formation of magnetite, and the phlogopite from alteration of other phases (Tomeoka and Buseck, 1990). Both high- and low-aluminum phyllosilicates were identified (Cohen and Kornacki, 1983). Kerridge (1964) identified the presence of a phyllosilicate with a serpentine layer spacing. Mössbauer analysis shows that approximately 7% of the total Fe (24.1 wt.% in this meteorite) is present in phyllosilicates (Herr and Skerra, 1968).

Dark inclusions that are “abundant” in Mokoia (Ohnishi and Tomeoka, 2002) are compositionally similar to the host meteorite but are finer-grained and contain less phyllosilicates, presumably due to dehydration by shock-induced thermal metamorphism. It is assigned to subtype CV3.0–3.2 because it appears to be a breccia (Krot et al., 1998, 2000), containing a range of lithologies (Guimon et al., 1995). It contains 3.2 wt.% magnetite by Mössbauer analysis (Bland et al., 2000) or 4.1 wt.% by thermogravimetry (Watson et al., 1975). It contains 0.54 wt.% C (Alexander et al., 2007), or 0.8 wt.% C, and 21.5% Fe in its matrix (Wood, 1967b).
A.8. NWA 3118 (CV3)

This CV3 chondrite shows, in thin section, curvilinear bands of olivine grains (Fa32–36) enclosing masses of fine-grained Fe-olivine (Fa42–58), pyroxenes, and sulfides (Russell et al., 2005). Many types of CAIs are present; no metal was observed in the matrix although some chondrules contain fresh metal; at least one dark inclusions is also present (Russell et al., 2005).

A.9. QUE 93744 (CV3)

The interior of this meteorite is dark-brown to black fine-grained, with abundant oxidation scattered throughout, and with some small light-gray inclusions (Satterwhite and Mason, 1995). A thin section shows numerous chondrules and irregular aggregates in a black matrix which contains accessory amounts of Fe-Ni-meteorite and troilite (Satterwhite and Mason, 1995). Most chondrule olivine is close to Fa90, but ranges up to Fa110; pyroxene composition is Fs1-2 (Satterwhite and Mason, 1995). The matrix consists largely of Fe-rich olivine, about Fa90 (Satterwhite and Mason, 1995).

A.10. Vigarano (CV3.2–3.3 – reduced subgroup)

It contains 48.9 vol.% chondrules, 5.4 vol.% AOIs, 5.3 vol.% CAIs, 2.1 vol.% lithic and mineral fragments, 34.5 vol.% matrix, 1.1 vol.% metal, 1.6 vol.% sulfides, and 0.3 vol.% magnetite, by optical point counting (McSween, 1977). It contains 34.5 vol.% matrix according to Alexander et al. (2007). May et al. (1999) found 1.7% CAIs by area. Many chondrules and chondrule fragments retain fine-grained rims which are composed largely of FeO-rich olivine (Abreu and Brearley, 2002). Many olivine grains contain a high density of nanometer-size inclusions, most of which are amorphous, and some of which contain amorphous carbon or poorly graphitized carbon (Abreu and Brearley, 2002). Matrix and chondrule rims average Fe/(Fe + Mg) of 0.59 and 0.65, and wt.% S of 0.16 and 0.30, respectively (Zolensky et al., 1993). It contains 28.8% Fe in its matrix (Wood, 1967b). Olivine and pyroxene compositions average Fa5.6 and Fs1.6, respectively (McSween, 1977). Matrix olivine compositions are fairly homogenous and cluster around Fa52 (Mason, 1983). Chondrule olivine grains (Fa32–36) enclosing masses of fine-grained Fe-rich olivine (Fa42–58) are both more Fe-rich than Allende; CAI spines contain 18–25% FeO (Murakami and Ikeda, 1994). It contains ~60 vol.% matrix that is dominated by ferroan olivine; fine-grained Al-spinel is also common in the matrix (Murakami and Ikeda, 1994).

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2012.07.007.

References