Spectral reflectance properties of carbonaceous chondrites: 8. “Other” carbonaceous chondrites: CH, ungrouped, polymict, xenolithic inclusions, and R chondrites

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

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

Abstract

We have analyzed reflectance spectra (0.3–2.5 μm) of a number of ungrouped or tentatively grouped carbonaceous chondrites (CCs), possible CC-type xenoliths in an aubrite (Cumberland Falls) and a howardite (PRA 04401), a CH chondrite (PCA 91467), a CC polymict breccia (Kaidun), and some R chondrites. The best approach to analysis relies largely on characterizing spectrally active phases – i.e., those phases that contribute diagnostic absorption features, involving absorption band wavelength position, band depth, shape of absorption features, combined with albedo and spectral slope. Mafic silicate (hydrous and/or anhydrous) absorption features are ubiquitous in the CCs and R chondrites we have examined. Combining information on these features along with albedo and spectral slopes allows reasonable inferences to be made concerning their uniqueness. Reflectance spectra of Coolidge show contributions from both olivine and Fe oxyhydroxides (from terrestrial weathering), and its high reflectance and mafic silicate band depths are consistent with a petrologic grade >3 and inconsistent with CVs. The CC nature of the Cumberland Falls inclusions from spectral analysis is inconclusive, but they do exhibit spectral features consistent with their overall mineralogy. DaG 430, which has petrologic characteristics of both CV and CK chondrites, has a spectrum that is not fully consistent with either group. The spectrum of EET 96029 is consistent with some, but not all CM2 chondrites. GRO 95566, a meteorite with some affinities to CM2s, most resembles the Renazzo CR2 chondrite, consistent with their similar mineralogies, and its spectral properties can be related to its major mineralogic characteristics. Spectra of Kaidun are most consistent with CR chondrites, which form the bulk of this meteorite. The reflectance spectrum of MCY 92005 is consistent with its recent classification as a CM2 chondrite. The R3 chondrite MET 01149 shares many characteristics with CKs, but differs in terms of its slightly red slope and 2 μm region absorption feature. The combination of high reflectance, deep 1 μm band and, to a lesser extent, slightly red slope and weak 2 μm region absorption band, distinguishes PRE 95404 from CV3s, to which it was initially assigned. The LAP 04840 R6 spectrum is dominated by olivine, consistent with a petrologic grade >3. Its reflectance is somewhat lower than for the R3 chondrites, and falls within the range of many CCs. Its most characteristic feature is the metal–OH absorption bands in the 2.3 μm region. Analysis and assignment of PCA 91467 (CH3) is complicated by the presence of terrestrial weathering products. Its red spectral slope is consistent with its high metal content. Reflectance spectra of the howardite PRA 04401, which contains ~40% CM2-like inclusions, is dominated by the howardite’s pyroxene absorption bands, and expected CM2-type absorption bands near 0.7 and 1.1 μm are not seen. The CC xenoliths do reduce overall reflectance and pyroxene absorption band depths significantly, and probably add an overall red slope, when compared to inclusion-free howardites. QUE 99038, which has been linked to CM2, CO, or CR chondrites is not spectrally consistent with any of these groups. The 2 μm band, high overall reflectance, and dominant olivine absorption band are all generally inconsistent with CM2 and CR2–3 chondrites. It resembles the CO3 chondrite ALH 77003 in the 1 μm region, but differs in the 2 μm region. The red-sloped, nearly featureless spectrum of Tagish Lake is unique among carbonaceous chondrites. It probably arises from the highly aromatic nature of the organic component and its intimate association with the phyllosilicate-rich matrix, which makes up a high proportion of this meteorite. Our results suggest that the meteorites included in this study can usually be determined to be either unique or to be placed with a reasonable degree of confidence into established CC groups. Our analysis has also provided

* Corresponding author. Fax: +1 204 774 4134.
E-mail addresses: e.cloutis@uwinnipeg.ca (E.A. Cloutis), pierre.hudon@mcgill.ca (P. Hudon), takahiro_hiroi@brown.edu (T. Hiroi), gaffey@space.edu (M.J. Gaffey).
1 Present address: Department of Mining and Materials Engineering, McGill University, 3610 rue Université, Montreal, QC, Canada H3A 2B2.
1. Introduction

Carbonaceous chondrites (CCs) have been the subject of many spectral reflectance studies because they are an important group of meteorites for understanding the origin and evolution of the Solar System. CCs include members, subgroups/grouplets and individual members that exhibit different degrees of aqueous and/or thermal alteration, but are generally characterized by an overall dark appearance. They are of astrobiological importance because some of their carbon-bearing phases are organic in nature and include many biological precursor molecules (e.g., Nagy, 1975). They may also have an important source of water for the proto-Earth (e.g., Chyba and Sagan, 1992; Morbidelli et al., 2000; Marty, 2012; Trigo-Rodriguez and Martin-Torres, 2012).

We have undertaken a spectral reflectance study of CCs to determine their range of spectral variability, to search for spectral similarities or differences between CC classes, to identify absorption features or other spectral properties that are diagnostic of constituent phases, to better elucidate the relationships between CC mineralogy, structure, and spectra, and to inform the search for CC parent bodies.

This is the eighth paper in a comprehensive examination of the spectral reflectance properties of CCs. Previous papers in this series have dealt with the largest and most agreed-upon CC groups: CI, CM, CR, CO, CV, CK, as well as a group of CCs that exhibit evidence of aqueous alteration followed by thermal metamorphism (Cloutis et al., 2011a,b). In addition to these main groups, there exist a number of smaller grouplets and individual CCs that do not easily fit into existing classification schemes, and these are the subject of the current paper. It should be noted that our analysis of “other” meteorites is by no means complete, as carbonaceous or carbon-rich clasts are known to exist in many meteorite types (e.g., Bunch and Rajan, 1988; Rubin et al., 2005).

2. Carbonaceous chondrite classifications

The criteria used to define CC classes were discussed in Cloutis et al. (2011a), and are briefly reviewed here. CCs as a group were first defined by Mason (1962) as “stony meteorites characterized by the presence of an appreciable amount of carbonaceous material other than free carbon (diamond and graphite)”. In his classification, petrologic type 1 CCs are made up predominantly of largely amorphous hydrated magnesium-iron silicate, hydrated magnesium sulfate, and magnetite. Type 2 CCs consist largely of a serpentine groundmass impregnated with carbonaceous material enclosing variable amounts of olivine and minor enstatite in the form of chondrules. Type 3 CCs consist in large part (~70%) of olivine with minor amounts of pyroxene (5–10%), magnetite (~5%), and troilite (~6%); Fe–Ni metal may be present in accessory amounts (Mason, 1962).

Newer methods that have been developed for discriminating CCs from other types of meteorites are more composition-based, and involve elemental ratios, bulk composition, and oxygen isotopic ratios (Table 1; e.g., van Schmus and Wood, 1967; van Schmus and Hayes, 1974; Wasson, 1974, 1985; McSween, 1979; Dodd, 1981). Compositional parameters that are useful for discriminating different CC groups and that may also translate into measurable spectral differences include iron oxidation state (oxidation increasing in the general sequence: CH(?) < CR < CV < CO < CK < CM < CI (Brearley and Jones, 1998), water content, and abundance of reduced carbon (Roy-Poulsen et al., 1981). Recent summaries of meteorite classifications can be found in Weisberg et al. (2006) and Brearley (2006).

Petrologic criteria such as chondrule size, texture, and matrix abundance may not be useful for discriminating different CC parent bodies, as textures would be largely destroyed during regolith evolution. However, other discriminating criteria may persist; these include the higher content of dark matrix material, lower bulk Fe, and ~2 times more C and H\textsubscript{2}O in CVs than COs (van Schmus, 1969; van Schmus and Hayes, 1974; McSween, 1977a); lower mafic silicate Fe content and higher metal contents in CRs than other CCs (Bischoff et al., 1993); and higher abundance of refractory inclusions in COs and CVs as compared to other CCs (Brearley and Jones, 1998). There are also correlations between organic matter (C, H, N abundances) and clay contents with extent of terrestrial aqueous alteration (Pearson et al., 2001). As with previous papers in this series, we focus our analysis on powdered CC reflectance spectra.

In this paper, we have examined CCs that do not easily fit into existing classification schemes, members of grouplets for which only one to a few spectra exist, polymict CCs, CC-type inclusions in other meteorites, and R chondrites. We use available mineralogic information for these samples in our analysis of their reflectance spectra and compare them, when appropriate, to spectra of other CC groups or meteorites for which possible linkages exist.

3. Experimental procedure

The meteorites included in this study are described in Table 2. Our spectral data base incorporates existing spectra from the RELAB data base (http://www.planetary.brown.edu/relab/), many of which have not been compared or analyzed in detail, reflectance spectra from other sources (Johnson and Fanale, 1973; Gaffey, 1974, 1976), and new spectra acquired for this study that have been measured at the NASA RELAB Facility at Brown University.
and the Planetary Spectrophotometer Facility at the University of Winnipeg. Our analysis is focused on the 0.3–2.5 μm interval.

The reflectance spectra subjected to detailed analysis were measured at the NASA-supported RELAB facility were acquired at i = 30° and e = 0° in bidirectional reflectance mode relative to halon for the ~0.3–2.5 μm region at 5 nm intervals, and corrected for minor irregularities in halon’s absolute reflectance in the 2.0–2.5 μm region. Details of the RELAB facility are available on the RELAB web site (http://www.planetary.brown.edu/relab/). Reflectance spectra measured at the University of Winnipeg Planetary Spectrophotometer Facility (PSF) were acquired with an ASD FieldSpec Pro HR spectrometer from 0.35 to 2.5 μm at i = 30° and e = 0° relative to Spectralon® and corrected for minor reflectance irregularities in the 2.0–2.5 μm region as well as detector offsets at 1.00 and 1.83 μm. Details of PSF are available on the PSF web site (http://psf.uwinnipeg.ca). Spectra acquired at the PSF were measured with a lampblack-coated aluminum mask (with a 5 mm diameter central hole) placed over the samples and Spectralon® measured with a lampblack-coated aluminum mask (with a 5 mm diameter central hole) placed over the samples and Spectralon® measured at the NASA-supported RELAB facility were acquired at the PSF were measured with a lampblack-coated aluminum mask (with a 5 mm diameter central hole) placed over the samples and Spectralon®.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Type/description</th>
<th>Grain size</th>
<th>RELAB File ID</th>
<th>Source of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolidge</td>
<td>C4 ungrouped CV affinities</td>
<td>&lt;150 μm</td>
<td>mgp126</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;74 μm</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>74–147 μm</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>147–405 μm</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Cumberland Falls</td>
<td>Aubrite</td>
<td>&lt;74 μm</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;74 μm</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>DaG 430</td>
<td>C3-ungrouped CK, CV affinities</td>
<td>&lt;125 μm</td>
<td>c1mp127</td>
<td></td>
</tr>
<tr>
<td>EET 96029</td>
<td>C2 CM affinities</td>
<td>&lt;125 μm</td>
<td>c1mp115</td>
<td></td>
</tr>
<tr>
<td>GRO 95566</td>
<td>C2-ungrouped CM2 affinities</td>
<td>&lt;125 μm</td>
<td>c1mp60</td>
<td></td>
</tr>
<tr>
<td>Kaidun</td>
<td>Polymict breccia</td>
<td>&lt;125 μm</td>
<td>c1ma73</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;45 μm</td>
<td>c1ma74</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45–100 μm</td>
<td>c1ma75</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100–250 μm</td>
<td>c1ma76</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;250 μm</td>
<td>c1ma98</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;125 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCY 92500</td>
<td>C2-ungrouped CM xenolith-bearing</td>
<td>&lt;45 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MET 0149</td>
<td>R3 CH3</td>
<td>&lt;75 μm</td>
<td>c1php45</td>
<td></td>
</tr>
<tr>
<td>PCA 91467</td>
<td>CH3</td>
<td>&lt;75 μm</td>
<td>c1php49</td>
<td></td>
</tr>
<tr>
<td>PRA 04401</td>
<td>Howardite:</td>
<td>&lt;45 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45–90 μm</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90–290 μm</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>PRE 95404</td>
<td>R3 or CV3</td>
<td>&lt;125 μm</td>
<td>c1mt47</td>
<td></td>
</tr>
<tr>
<td>QUE 99038</td>
<td>C2-ungrouped CM/CR affinities</td>
<td>&lt;75 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tagish Lake</td>
<td>C2-unique CM2/C2/C1 affinities</td>
<td>&lt;125 μm</td>
<td>c2mt11</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;125 μm</td>
<td>c2mt12</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;125 μm</td>
<td>c1mt2550</td>
<td></td>
</tr>
</tbody>
</table>

* For spectra acquired at facility other than RELAB.
* Xenolithic carbonaceous chondritic inclusions (whole rock spectra also measured).
* Includes lithologies classified as C-ungrouped, CR, EH3–5, CV3, CM1–2, R, C1-ungrouped, and C2-ungrouped.
* Contains ~40 vol.% carbonaceous chondrite inclusions; whole rock spectra measured.
* ET01-B subsample.
* PMO Sc subsample.
* Tagish7 subsample, <125 μm powder pressed into pellet for laser irradiation.

After fitting a straight line continuum tangent to the spectrum on either side of an absorption feature of interest. Band centers were calculated the same way as band minima after continuum removal. The RELAB and PSF reflectance spectra discussed in this paper are provided as an online Supplementary material.

4. Results

This study includes a diverse suite of meteorites that are either unclassified or of uncertain affinity for a variety of reasons. Some of the ungrouped meteorites included in this study may be members of established groups, but have been insufficiently studied for definitive classification. Where appropriate, we have grouped some meteorites together in our discussion.

4.1. Coolidge (C4-ungrouped; affinities to CV)

Coolidge is widely considered to be a C4 chondrite, with affinities to the CV group (CVs subgroup). Optical point counting gives 67.4 vol.% chondrules and chondrule fragments, 4.0 vol.% AOIs, 2.5 vol.% CaIs, a trace amount of lithic and mineral fragments, 17.6 vol.% matrix, 3.7 vol.% metal, 2.6 vol.% sulfides, 3.4 vol.% magnetite, and 1.8 vol.% hematite intimately intergrown with the magnetite (McSween, 1977b). Noguchi (1994) describes Coolidge as consisting of chondrules, AOIs, CAIs, metal and sulfide grains, isolated silicate minerals, and fine-grained matrix composed mostly.
of fragmental olivine (Fa$_{20-30}$) and minor pyroxene, which is likely chondrule fragments, and abundant Fe–Ni-metals and sulfides (Noguchi, 1994). Chondrules claviforms cluster around Fa$_{14}$ (van Schmus, 1969; McSween, 1977b; Scott and Taylor, 1985; Noguchi, 1994). Low-Ca pyroxene is somewhat heterogeneous (Fs$_{1-15}$; average Fs$_{11}$Wo$_{21.1}$) (McSween, 1977a,b; Noguchi, 1994). Opaque phases are largely kamacite and troilite (Scott and Taylor, 1985). Fe–Ni-metals and troilite are present in chondrules (Noguchi, 1994). In contrast to McSween (1977b), Fisher and Burns (1991) found that Coolidge contains no magnetite by Mössbauer spectroscopy, but does contain Fe oxyhydroxides resulting from terrestrial weathering. CAIs are very Fe-rich in comparison to CV CAIs (van Schmus, 1969; McSween, 1977b) or 0.19 wt.% (Jarosewich, 1990). It was classified as subtype CV3.0–3.6. The highest metamorphic grade CV is likely Allende (CV > 3.6; Bonal et al., 2006). However, we suspect that this feature in the Allende spectrum may be an artifact, as it only appears in the Gaffey (1974) Allende spectra – the other RELAB Allende spectra are dominated by olivine (Fig. 1d).

We can compare Coolidge to other CVs, particularly the higher metamorphic grade ones and CV$_R$ chondrites. The highest metamorphic grade CV is likely Allende (CV > 3.6; Bonal et al., 2006). Multiple spectra of Allende are available. Compared to Coolidge (Fig. 1c), they are darker and more red-sloped, and do not exhibit the bow-shaped spectrum of Coolidge beyond 0.75 μm. The difference in reflectance may be a function of aggregation of opaques with increasing thermal metamorphism, as Allende has a higher C content than Coolidge (0.27–0.39 wt.% versus 0.01–0.19 wt.%; Halbout et al., 1986; Jarosewich, 1990; Pearson et al., 2006), or the terrestrial-produced Fe oxyhydroxides in Coolidge. Allende also contains magnetite (1.2 vol.%; McSween, 1977b).

The 1 μm region absorption feature of Coolidge is likely real, as it also appears in the Johnson and Fanale (1973) Coolidge spectra. However, we suspect that this feature in the Allende spectrum may be an artifact, as it only appears in the Gaffey (1974) Allende spectrum – the other RELAB Allende spectra are dominated by olivine (Fig. 1d).

When Coolidge is compared to available CV$_R$ spectra (Fig. 1e), such as Leoville and Vigarano (both CV$_R$ 3.1–3.4; Bonal et al., 2006), the CVs are again darker than Coolidge, but more similar in terms of overall slope (neutral to blue) and position of local maxima near 0.75 μm. The continuum-removed spectra (Fig. 1f) are diverse. The Gaffey (1974) Leoville and Vigarano spectra both show an apparent absorption feature near 0.9 μm (like Coolidge) while the RELAB and PSF Vigarano and Leoville spectra do not.

Coolidge can also be compared to laboratory heated samples of Allende (Fig. 1g). With increasing temperature (above ~900 °C), Allende reflectance systematically increases, likely due to loss/aggomeration of opaques, and mafic silicate absorption bands become more apparent. Pre-existing poorly crystalline or amorphous silicates are gradually converted to more crystalline forms. A 2 μm region pyroxene band becomes more apparent with increasing temperature, although this is likely due to the loss of opaques rather than formation of pyroxene from other phases, as the 1 μm region absorption band does not show a shift toward the pyroxene field (Fig. 1h).

The data collectively suggest that Coolidge has a spectrum with contributions from both terrestrial Fe oxyhydroxides and olivine. The higher overall reflectance of Coolidge is consistent with the trend found for other CCs, where increasing reflectance is associated with increasing thermal metamorphism. The cause of the bow-shaped spectrum of Coolidge is not obvious, but is consistent with magnetite. Spectrally, Coolidge differs in many respects from the available CV3.0–3.6 spectra, but differences in mafic silicate bands suggests that Coolidge’s spectrum is consistent with thermally metamorphosed CVs.

4.2. Cumberland Falls chondritic inclusions

Cumberland Falls is an enstatite aubrite (aubrite) that contains a number of black inclusions scattered heterogeneously throughout this meteorite (Neal and Lipschutz, 1981). These inclusions are of low petrologic type (<3; Neal and Lipschutz, 1981). An inclusion studied by Binns (1969) contained broken and intact chondrules up to 1 mm in diameter in a brownish isotropic glassy to turbid gray groundmass, and occasional ragged metal grains. He classified the inclusion as a primitive chondrite with possible affinities to LL chondrites. Major inclusion phases include olivine, pyroxene (Low-Ca, diopside, and jadeite), plagioclase feldspar, Fe–Ni metal, schreibersite, troilite, and other rare sulfides (Neal and Lipschutz, 1981). Olivine and pyroxene are the most common phases and both are low-Fe: most olivine is close to pure forsterite and most pyroxene is Fs$_{3-7}$. The inclusions were shocked during incorporation into the aubrite parent body (Neal and Lipschutz, 1981). We have included this material in the current paper because of the black appearance of the inclusions but note that trace element data does not match CCs (Verkouteren and Lipschutz, 1983).

Reflectance spectra of the Cumberland Falls host and inclusions are shown in Fig. 2a and b. The unsorted powdered sample of Cumberland Falls is strongly blue-sloped with 22.5% reflectance at 0.56 μm. This relatively high reflectance is consistent with aubrites (Burbin et al., 2002). It also has a weak absorption band near 0.9 μm, attributable to small amounts of low-Fe$^2+$-bearing pyroxene in aubrites (Watters and Prinz, 1979); a second expected absorption band near 1.9 μm is overprinted by likely water-bearing alteration phases. The inclusions have reflectance of 6.5–8.5% at 0.56 μm, consistent with values for CCs. The finer-grained fraction is brighter and less red-sloped than the coarser fraction; this difference in slope is not consistent with how CC spectra vary with grain size as determined by Johnson and Fanale (1973). The continuum-removed spectra (Fig. 2c) show a number of absorption features. Pyroxene appears to be spectrally dominant – its wavelength position (0.93–0.95 μm) suggests contributions from phases besides low-Ca pyroxene. Jadeite spectral contributions are suggested
by the absorption features near 1.10–1.15 μm, and a flattening of the spectral slope in the 0.7 μm region; jadeite can also contribute to the 0.9 μm region feature. The 1.10–1.15 μm feature could also be attributed to phyllosilicates, although phyllosilicates have not been identified in Cumberland Falls inclusions. Magnetite could also account for the 1.10–1.15 μm feature. Spectral contributions by olivine are suggested by the bands/inflections near 1.05 μm and 1.3 μm. The absorption feature near 1.35 μm is likely due to some hydrated phase; this may be due to terrestrial weathering, as native phyllosilicates have not been noted in Cumberland Falls inclusions (Neal and Lipschutz, 1981). Fe³⁺-bearing weathering products could also account, in part, for the 0.9 μm absorption feature.

Fig. 1. (a) Reflectance spectrum of a <150 μm powder of the Coolidge C4 chondrite measured by Gaffey (1974) using an integrating sphere and digitized by RELAB. (b) Continuum-removed spectrum from (a). (c) Coolidge versus various RELAB spectra of Allende. (d) Continuum-removed spectra from (c). (e) Coolidge versus CV₃ spectra from RELAB (Vigarano), Gaffey (1974; Leoville (IS)), and PSF (Leoville 30/0). IS = integrating sphere spectrum. (f) Continuum-removed spectra from (e). (g) Coolidge spectrum versus RELAB spectra of the Allende CV₃ heated to different temperatures. (h) Continuum-removed spectra from (g). Linear vertical offsets applied to some of the continuum-removed spectra for clarity are indicated (f and h).

4.3. DaG 430 (C3-ungrouped; affinities to CK, CV)

This meteorite has been classified as a C3 ungrouped chondrite with olivine and pyroxene compositions of Fa₀.₅–₃₀.₁ (average Fa₂₀.₂) and Fs₁.₁–₂₀.₆ (average Fs₁₇.₉), respectively (Grossman, 1999). It exhibits metal grains in thin section (Grossman, 1999). It may be paired with DaG 055, 056, and 429; the following description relates to DaG 055. The chondrules and mineral fragments consist of unequilibrated olivines (Fa₀.₄–₃₂; mean Fa₁₄.₉) and pyroxene (Fs₀.₆–₆; mean Fs₃.₈), while the matrix olivine is highly equilibrated (Fa₂₀–₃₁) (Weber et al., 1996). This suggests a petrologic subtype lower than 3.5 (Weber et al., 1996). The unequilibrated lithic mafic silicates and equilibrated matrix olivine
compositions are similar to CK < 3.5 chondrites (Weber et al., 1996). It also has low modal abundance of CAIs and AOIs, similar to CK chondrites (Weber et al., 1996). Its chondrule size and matrix texture are similar to CV chondrites, while its oxygen isotopes fall between the CV and CK groups (Weber et al., 1996).

Spectrally, DaG 430 (Fig. 3a) shows well-defined mafic silicate absorption bands, including contributions from olivine (band near 1.05 μm and inflections near 0.85 and 1.25 μm), and low-Ca pyroxene (inflection near 0.9 μm and band near 1.95 μm). Even though CAI abundances are low (Weber et al., 1996), CAI spinel may be contributing to the suppressed rise in reflectance longward of ~2.1 μm, which would be expected if only pyroxene was contributing to this spectral region.

In comparison to the less equilibrated CV and CK chondrites, DaG 430 has similar overall reflectance and 1 μm region absorption feature to MET 01149 (discussed below). The 2 μm region of DaG 430 shows a greater contribution from pyroxene and spinel than MET 01149. The CK4 chondrites are less like DaG 430, exhibiting a 1 μm olivine-like absorption feature, but a weak or nonexistent 2 μm feature (Cloutis et al., 2012e).
Some CV3 chondrite spectra also show similarities to DaG 430 (Fig. 3b). Similar-sized CV powder spectra are uniformly darker than DaG 430 (Cloutis et al., 2012d), but some have similar spectral features to DaG 430, in particular their 1\lmu m region absorption features have similar position and shape, the 2\lmu m region also shows contributions by pyroxene and Fe\textsuperscript{2+}-bearing spinels, and overall slopes are also similar. These data suggest that, at least spectrally, DaG 430 is most similar to CV3 rather than CK4 or R3 spectra.

4.4. EET 96029 (C2; affinity to CM)

EET 96029 was described as having a black interior with small white inclusions (McBride and McCoy, 1998). It contains numerous small chondrules, larger CAIs, and mineral fragments in a black matrix; trace amounts of metal and troilite are present (McBride and McCoy, 1998). The matrix appears to consist of serpentine; olivine composition ranges from Fa0 to Fa39, with most Fa0–2, and pyroxene ranges from Fs2 to Fs5, leading to a classification as a C2 chondrite (McBride and McCoy, 1998). It contains P-bearing sulfides, like other CM chondrites (Nazarov et al., 2009). It was recently reclassified as CM2 (Righter, 2010).

EET 96029 differs from most CM2 chondrites in not exhibiting a prominent 0.75\lmu m region Fe\textsuperscript{2+}–Fe\textsuperscript{3+} phyllosilicate charge transfer band; however a few CM2s also do not exhibit this band (Fig. 4a). In particular one spectrum of Murchison (shown in Fig. 4a) and ALH 84033 have some features in common with EET 96029; i.e., similar spectral shape, overall reflectance, spectral slope, lack of 0.7 \mu m absorption feature, and local reflectance maximum near 0.8 \mu m. Murchison, like many other CM2s, show spectral variability, and hence not all Murchison spectra match EET 96029 (Cloutis et al., 2011b). The continuum-removed spectra (Fig. 4b) show expected variability. The EET 96029 spectrum shows evidence of olivine (1.25 \mu m absorption feature) and Fe\textsuperscript{2+}-bearing serpentine (0.9 and 1.1 \mu m absorption features). The broad 1 \mu m region absorption feature of ALH 84033 also suggests contributions from olivine and serpentine. The shape of the continuum-removed Murchison spectrum suggests a larger contribution from olivine (band center near 1.08 \mu m) than serpentine. The spectral shape, slope, absorption features and overall reflectance of EET 96029 are all consistent with the spectral properties of CM2s and indicate contributions from both serpentine and olivine.

4.5. GRO 95566 (CM2 or C2-ungrouped)

GRO 95566 was recently reclassified from a C2 to a C2-ungrouped chondrite (Righter, 2008). Some chondrules are rusty; it contains numerous small chondrules, some irregular aggregates, and many small silicate grains in a black matrix; trace amounts of metal and troilite are present as minute grains (McBride and Mason, 1997b). The silicate grains are almost entirely olivine near Fa0, with a few more Fe-rich grains up to Fa35 (Choe et al., 2010); a little pyroxene of Fs2–4 is also present (Choe et al., 2010), and the matrix appears to consist largely of Fe-rich serpentine (McBride and Mason, 1997b). Chondrule mesostasis has been altered to phyllosilicates (Choe et al., 2010). Clayton and Mayeda (1999) determined that GRO 95566 appears to be a CM2 chondrite, but has exceptional oxygen isotope composition. In comparison to CM2 chondrites, GRO 95566 is less altered (Choe et al., 2010).
The spectrum of GRO 95566 is consistent with a carbonaceous meteorite containing Fe-poor mafic silicates (Fig. 5a): reflectance is ~5% in the visible region, and absorption bands are weak. Mineralogically, it is most similar to CR chondrites in terms of low Fe-olivine and presence of serpentine. Spectrally, it is most similar to the Renazzo CR2 fall in overall reflectance, spectral shape and slope, and a weak 1 μm region absorption feature. It is much darker than other CR2s, which may reflect differences in opaque abundances and distribution.

The weathering grade of GRO 95566 is A/Be, similar to other Antarctic CR2s (Cloutis et al., 2012a). However, we believe that even low weathering grades can add spectral features due to terrestrially-produced Fe oxyhydroxides, as their mafic silicates are Fe-poor and consequently have shallow mafic silicate absorption bands (Cloutis et al., 2012a). The continuum-removed spectra (Fig. 5b) show that Renazzo is most similar to GRO 95566 in terms of having a shallow 1 μm region absorption band with probably contributions from olivine (1.05 and 1.25 μm) and serpentine (0.9 and 1.1 μm). It differs from the other CR2 spectra, which have a narrower 1 μm region absorption feature and which have strong spectral contributions near 0.9 μm from Fe oxyhydroxides. Overall, GRO 95566 resembles the Renazzo CR2 chondrite, which is expected given similar mineralogy – particularly low-Fe olivine chondrules and mineral fragments and serpentine-dominated groundmass. This reiterates the fact that CC reflectance spectra can be variable and that silicate mineralogy can be roughly constrained from, in particular, the 1 μm region.

4.6. Kaidun (C-ungrouped, polymict breccia; predominantly CR with diverse xenoliths)

This meteorite is a complex breccia that appears to be mainly CR chondrite but containing clasts of several other carbonaceous chondrites (CV2, CM1-2), ordinary chondrites, and enstatite chondrites (EL3, EH3–5) (Ivanov, 1989; Krot et al., 2002; Kurat et al., 2004), as well as other unique lithologies (C1 and C2 type, Ca-rich achondrite, alkaline-enriched clasts) and impact melts (Zolensky and Ivanov, 2003). In the CR portion of the meteorite, matrix comprises ~70 vol.% and is composed mainly of phyllosilicates (predominantly smectite and serpentine), magnetite, carbonates, oxysulfides, and carbonaceous material (Ivanov, 1989; Golden et al., 1994). Some inclusions are composed of olivine (Fe0.3–38.4) and low-Ca pyroxene (Fs0.2–20 Wo0.1–4.5) (Ivanov, 1989). While it shares some chemical affinities with CR chondrites, it does not display recognizable CR petrologic features (Zolensky and Ivanov, 2003).

Multiple spectra are available for Kaidun (Fig. 6a). The increasing grain size series exhibits decreasing reflectance and bluer overall slope, consistent with other CCs (Johnson and Fanale, 1973). The <125 μm fraction spectrum has similar slope to the <45 μm spectrum, but overall reflectance is ~1% lower. The continuum-removed spectra (Fig. 6b) exhibit a number of absorption features in the 1 μm region, most noticeably in the larger grain size spectra. The relative lack of well-resolved absorption bands in the fine-grained spectra is consistent with the behavior exhibited by the CR2 chondrite Renazzo (Fig. 5a and b). The coarser grain size
spectra show a broad absorption feature in the 1 µm region with probable absorption bands near 0.7, 0.90–0.93, 1.0–1.1 µm, and 1.25 µm. The 0.7 µm feature is consistent with the abundant serpentine in Kaidun, and indicates that it is an Fe²⁺–Fe³⁺-bearing variety. The 0.90–0.93 µm feature is also consistent with serpentine, but could also be attributed to enstatite. The 1.0–1.1 µm feature can be attributed to magnetite, olivine, and/or serpentine. The 1.25 µm is uniquely attributable to olivine, which is present in CR chondrites. Overall, the fine-grained Kaidun spectra are consistent with CR chondrites, largely due to the low overall reflectance and lack of strong silicate absorption bands. The larger grain size spectra show better evidence of the various silicate components and possibly magnetite that comprise the bulk of Kaidun.

4.7. MCY 92500 (C2-unassigned; CM2)

This meteorite was classified as a C2 chondrite by Satterwhite and Mason (1993). The interior matrix is fine-grained, medium to dark gray, with abundant small white and gray inclusions and a few chondrules; oxidation is minor (Satterwhite and Mason, 1993). A thin section shows chondrules, irregular aggregates and small mineral grains in a black matrix; the minerals are mostly olivine with minor pyroxene (Satterwhite and Mason, 1993). Olivine compositions are mostly close to Fa0 with occasional Fe-rich grains up to Fa12, and pyroxene composition ranges from Fs1 to Fs5; the matrix appears to be largely Fe-rich serpentinite (Satterwhite and Mason, 1993). This meteorite was classified as not thermally metamorphosed because it exhibits an absorption feature near 0.7 µm, and band shape and strength in the 3 µm region is dissimilar to known thermally metamorphosed C chondrites (Hiroi et al., 1997). It was more recently classified as a CM2 (Righter, 2010).

Its reflectance spectrum (Fig. 7a) is similar to many CM2 chondrites in terms of all major spectral properties, such as overall reflectance, slope and 1 µm region absorption features. This is shown more clearly in Fig. 7b, where MCY 92500 and these CM2 chondrules all exhibit a 0.7 µm Fe²⁺–Fe³⁺ charge transfer serpentinite band, and 0.93 and 1.1 µm Fe²⁺ crystal field serpentinite bands. The expected olivine absorption bands near 1.05 and 1.25 µm are not apparent, likely due to overlaps from the adjacent serpentinite bands and the low olivine Fa content. The spectrum of MCY 92005 is consistent with other CM2 spectra discussed in more detail in Cloutis et al. (2011b).

4.8. R chondrites: MET 01149 (R3), PRE 95404 (R3), and LAP 04840 (R6)

MET 01149, PRE 95404, and LAP 04840 have been identified as R chondrites, and are discussed together here. MET 01149 was recently classified as an R chondrite on the basis of various petrologic and compositional criteria (Righter, 2010). The interior shows a medium-gray matrix with some gray and white clasts and chondrules, and very little weathering (McBride et al., 2003). A thin section shows well-defined chondrules in a matrix of finer-grained silicates, magnetite and abundant sulfide, and it is extensively shocked (McBride et al., 2003). It contains 25 vol.% chondrules, 7 vol.% opaques, 2 vol.% CAIs, and 66 vol.% matrix (Neff and Righter, 2006). Silicates are heterogeneous: olivine is Fa2–39 with many grains around Fa38 (McBride et al., 2003); Neff and Righter (2006) give olivine composition as ~Fa37.

PRE 95404 was tentatively classified as a CV3 by McBride and Mason (1997a), but it lacks the marked olivine composition peak at Fa₃₉, commonly present in C3 chondrites. It was later reclassified as an R3 chondrite (Imae and Zolensky, 2003; Righter, 2008). The interior is a gray crystalline mass with metal grains and light-colored chondrules (McBride and Mason, 1997a). An interior section shows numerous chondrules, chondrule fragments, irregular aggregates and silicate grains in a black matrix which contains a moderate amount of Fe-Ni-metal and sulfide (McBride and Mason, 1997a). Olivine composition is variable, Fa1–41, as is pyroxene, Fs7–21; the matrix consist largely of olivine with composition around Fa30 (McBride and Mason, 1997a). Imae and Zolensky (2003) identified R3 and R4 clasts in PRE 95404. Olivine composition ranges from Fa0 to Fa40 in the R3 clast, but is clustered around Fa35–40 in the R > 4 clast; low Ca and high Ca pyroxenes are both present, sulfides consist of pyrrhotite and pentlandite and mainly occur as opaque chondrules, and no metals are present (Imae and Zolensky, 2003).

R chondrites are characterized by highly oxidized (Fe-rich) olivine, and are distinguished from CK chondrites (which are also oxidized) by the absence of magnetite (Imae and Zolensky, 2003). Olivine is the major component of R chondrites, with lesser amounts of plagioclase feldspar, pyroxene, and abundant (6–10 wt.%) pyrrhotite and pentlandite (Schulze et al., 1994; Isa et al., 2010). The chondrule/matrix ratio for R chondrites is lowest among chondrites (Imae and Zolensky, 2003). CAIs and Fe-Ni metal are rare, and Fe²⁺-bearing spinels may be present (Rout and Bischoff, 2008; Isa et al., 2010). Pyroxene abundance decreases with increasing metamorphism.

Reflectance spectra of MET 01149 and PRE 95404 are shown in Fig. 8. Both spectra are characterized by high reflectance (15–19% at 0.56 µm), a well-defined olivine absorption band centered at 1.06 µm, and an additional absorption feature in the 2.1 µm region. The 2 µm region absorption feature suggests contributions from
low-Ca pyroxene and/or Fe-bearing spinels as it is broad and centered between ~2.1 and 2.2 μm (Cloutis et al., 2004). These spectra are similar to Rumuruti, another R3 chondrite (Burbine et al., 2003).

Compared to CV chondrites, PRE 95404 is consistently brighter for comparable size powder spectra, PRE 95404 is slightly red-sloped, as are a number of CVs (Cloutis et al., 2012d). PRE 95404 and CV chondrites show a well-defined olivine absorption feature near 1 μm. The 1 μm region band depth of PRE 95404 (16.3%) is greater than CVs (<10%) and comparable to Allende heated to >1100 °C (Cloutis et al., 2012d). The combination of high reflectance, deep 1 μm band and, to a lesser extent, slightly red slope and weak 2 μm region absorption band, distinguishes PRE 95404 from CV3s.

LAP 04840 is an R6 chondrite. The interior is a fine-grained crystalline matrix with black and white crystalline inclusions, and no evidence of rusting or metal (McBride and McCoy, 2006). In thin section, LAP 04840 is texturally heterogeneous, containing relict chondrules up to 1 mm, and 100–200 μm mineral grains and microcrystalline areas with 5–10 μm mafic silicate grains. It consists of FeO-rich olivine (Fa38), orthopyroxene (Fs30Wo1), and plagioclase feldspar (An7Or3). Hornblende comprises ~15% of the meteorite, with composition (wt.% of approximately 48% SiO2, 3% Na2O, 6% Al2O3, 16.5% MgO, 11% FeO, 10% CaO and <0.5% TiO2, MnO and K2O, and no Cl. Opaque minerals include troilite, pentlandite and chromite. The presence of hornblende and biotite is consistent with high temperature aqueous alteration at depth (Mikouchi et al., 2007). Other R6 chondrites do not contain hornblende or biotite (Isa et al., 2010), suggesting that an influx of water was required for the formation of the hydrated phases (Mikouchi et al., 2007).

Reflectance spectra of LAP 04840 and amphibole separates (Klima et al., 2007) indicate that identifying the presence of amphibole in LAP 04840 reflectance spectra below 2.5 μm is difficult because it has a weak Fe³⁺–Fe²⁺ charge transfer band, and the Fe²⁺ charge transfer band is overlapped by the stronger olivine Fe³⁺ charge transfer band. However, the amphibole separates and the <125 μm whole rock spectra (Klima et al., 2007) do show metal–OH combination bands in the 2.3–2.4 μm region that can be attributed to amphibole (Mustard et al., 1989).

Reflectance spectra of LAP 04840 measured at the PSF are shown in Fig. 9. They show similar behavior to the LAP 04840 spectra of Klima et al. (2007). Both the bulk and <250 μm spectra are dominated by olivine; the presence of hornblende/biotite is suggested by the weak absorption bands in the 2.3–2.4 μm region. Reflectance is somewhat lower than for the R3 chondrites, and falls within the range of many CCs. The most characteristic feature of LAP 04840 is the metal–OH absorption bands in the 2.3 μm region.

4.9. PCA 91467 (CH3)

PCA 91467 has been identified as a CH3 chondrite. The interior is dark brown to black and fine-grained, with a few small inclusions and extensive weathering (Marlow et al., 1993). A thin section shows a few chondrules, abundant pyroxene grains and a considerable amount of Fe–Ni-metal; it is severely weathered with limonitic staining (Marlow et al., 1993), although some portions appear to be unweathered (Bischoff et al., 1994). Most of the pyroxene is close to Fs0, but ranges up to Fs9 (Marlow et al., 1993). It is metal-rich with only a few chondrules (Bischoff et al., 1994). CAI abundance is below 1 vol.%, and the most abundant components are mineral and lithic fragments (Bischoff et al., 1994). A wide range of olivine (Fa0.5–4.5) and pyroxene (Fs1–46) compositions were found, but most are MgO-rich with peaks at Fa0.1 (olivine) and Fs0.5 (pyroxene) (Bischoff et al., 1994). It contains carbon–silicate aggregates, Fe–Ni-metal grains and abundant hydrated materials (Sugiura, 2000); all of the fine-grained matrix seems to be hydrated to some degree, along with some evidence of subsequent dehydration (Sugiura, 2000). Framboidal magnetite is present, again suggesting hydration (Sugiura, 2000). It also contains xenolithic clasts (Zolensky et al., 2009).

CH chondrites are among the most primitive meteorites within the carbonaceous chondrite suite (Hezel et al., 2003). They contain ~70 vol.% 20–90 μm-size chondrules and chondrule fragments, ~20 vol.% Fe–Ni metal (among the highest metal abundance of any C chondrite group), low Fe in the mafic silicates, low abundances of CAIs (<0.1–1 vol.%) and lack fine-grained interchondrule matrix (Krot et al., 2002, 2012; Hezel et al., 2003; Weisberg et al., 2006; Krot, 2008). Ferrous chondrules (Fe/(Fe + Mg) = 0.11–0.35) are also present (Krot et al., 2002). While CAIs are of low overall abundance, they are common because of their small size (Brearley and Jones, 1998). The constituent CAI minerals are all more Fe-rich on average than CAIs in CM and CV chondrites (Brearley and Jones, 1998), and common phases include grossite (CaAl2O4) and melilite, with accessory hibonite, spinel and perovskite (Brearley and Jones, 1998). CH chondrites contain completely hydrated matrix lumps (Krot et al., 2000) that contain magnetite, sulfides, and carbonates set in a phyllosilicate matrix that is composed of serpentine and saponite (Greshake et al., 2002). The phyllosilicates are Fe-rich (Fe/(Fe + Mg) = ~0.62 (Greshake et al., 2002). AlH 85085 (a probable CH chondrite) contains ~10 vol.% obvious chondrules, 62 vol.% other silicate particles (~90% pyroxene of ~Fs4 and 10% olivine of mostly Fs4–6.2), ~0.1 vol.% CAIs, 23 vol.% opaque minerals, and ~4 vol.% CI clasts (Grossman et al., 1988). Another analysis of AlH 85085 gives 70 vol.% silicate fragments, 20 vol.% Fe–Ni metal,
5 vol.% matrix lumps that are phyllosilicate-rich, 5 vol.% chondrules, 0.4 vol.% troilite, and 0.1 vol.% magnetite (Scott, 1988). There are indications that CHs are related to CR and CB chondrites in terms of at least their region of formation (Weisberg et al., 1995).

The reflectance spectrum of PCA 91467 is shown in Fig. 10a. PCA 91467 is characterized by a red-sloped spectrum with 10% reflectance at 0.56 μm and 14% reflectance at the 0.8 μm peak. It exhibits two absorption features near 0.9 and 1.95 μm. The continuum-removed spectrum (Fig. 10b) shows a 3% deep absorption feature centered near 0.93 μm. It appears to be asymmetric with a shallower long wavelength wing. This feature is consistent with low-Ca pyroxene, although the band is located at slightly longer wavelengths than would be expected for low Fe-content low-Ca pyroxene (Cloutis and Gaffey, 1991). The shallow absorption feature centered near 1.93 μm is also consistent with low-Ca pyroxene. The identification of abundant terrestrial weathering products (limonitic staining; Marlow et al., 1993) and the steep reflectance dropoff shortward of ~0.6 μm, suggests that the 0.9 μm feature includes spectral contributions from terrestrial weathering products, particularly when coupled to the low Fs content of the pyroxene. The 1.9 μm region absorption feature may also contain contributions from terrestrial weathering products, as well as the common hydrated silicates it contains (Sugiura, 2000). The red slope of this meteorite is likely attributable to a combination of its abundant metal and terrestrially-produced Fe oxyhydroxides. Given the composition of this meteorite, it seems likely that PCA 91467 is a reasonable spectral analogue for CH3 chondrites, but terrestrial weathering has likely led to an increase in spectral slope below 0.6 μm, and a deepening of the 0.9 and 1.9 μm region absorption features. Its overall reflectance falls within the range for most CCs. A reflectance spectrum of a chip of PCA 91467 exhibits maximum reflectance of ~12% at 0.3 μm (Trigo-Rodriguez, personal communication, 2012), suggestive of less weathering products in his sample, reinforcing the observation that weathering is heterogeneous in this meteorite.

4.10. PRA 04401 (howardite)

PRA 04401 is a howardite that contains ~60% CM2 clasts (McBride et al., 2007; Herrin et al., 2010, 2011). The original description of PRA 04401 is “a groundmass of comminuted pyroxene and plagioclase (up to 0.5 mm) with fine- to coarse-grained basaltic clasts ranging up to 5 mm” (McBride et al., 2007). Its orthopyroxene is compositionally diverse (Fs16–60Wo1–3) and plagioclase feldspar composition is An87–90 (McBride et al., 2007). Our sample of PRA 04401 contained ~40% visible CM2 clasts, ranging in size up to ~4 mm.

Fig. 11a shows reflectance spectra of PRA 04401 for different grain sizes and Fig. 11b shows the <45 μm fraction of PRA 04401 compared to other <45 μm inclusion-free howardites. Comparison of these spectra indicates that the CM2-type inclusions in PRA 04401 cause reflectance to decrease. With increasing grain size, the PRA 04401 spectra become darker and more blue-sloped, consistent with the behavior of other CM2 spectra (Johnson and Fanale, 1973; Cloutis et al., 2012b). However, expected CM2-type absorption bands, near 0.7, and 1.1 μm are not apparent in the PRA 04401 spectra, even given its high CM2 abundance. With the current spectral data we are not able to ascertain the spectral properties of the CM2 type inclusions, beyond the fact that they are
The interior is charcoal gray with numerous chondrules and light and dark gray crystalline material (McBride et al., 2001). A thin section shows a few small chondrules, mineral grains and CAIs set in a black matrix; rare metal and sulfide grains are present (McBride et al., 2001). Olivine compositions are Fa1–39, with many Fa0–3; the matrix consists predominantly of an Fe-rich serpentine, and it was classified initially as a CM2 chondrite (McBride et al., 2001). It is an aqueously altered chondrite, but differs from CMs and it was classified initially as a CM2 chondrite (McBride et al., 2001). It is an aqueously altered chondrite, but differs from CMs because its chondrules are larger; they are closer to CR chondrules in size (Huber et al., 2006; Choe et al., 2010). However, unlike CR chondrites, QUE 99038 contains little metal. Refractory lithophiles are close to the CO range (Huber et al., 2006). The anomalous bulk composition and other petrologic features led to its being classified as a devolatilized petrologic type 2 ungrouped chondrite by Huber et al. (2006) and Choe et al. (2010).

The spectrum of QUE 99038 is shown in Fig. 12a. It is unlike most CM2 chondrites in terms of having higher reflectance and a well-defined 2 μm region absorption feature (Cloutis et al., 2012b). Superficially, it resembles some CO chondrites (e.g., ALH 77003) in having a well-defined olivine-type absorption band, and a 2 μm region absorption feature. While the overall reflectance of QUE 99038 is similar to COs, the 2 μm region absorption band does not resemble that of COs, whose spectra in this region show evidence of Fe²⁺-bearing spinel. The 2 μm region absorption band center of QUE 99038 is near 1.98 μm, which is suggestive of pyroxene (whose presence in this meteorite is undocumented). The continuum-removed 1 μm region (Fig. 12b) shows an absorption feature centered near 1.06 μm, and a prominent inflection near 1.25 μm, both consistent with olivine. The presence of pyroxene is also suggested by a weak inflection near 0.9 μm. The presence of phyllosilicates (serpentinite) likely accounts for the asymmetric appearance of the absorption feature near 1.1 μm, and may also be contributing to the weak inflection near 0.9 μm. The 2 μm band, high overall reflectance, and dominant olivine absorption band are all generally inconsistent with CM2 and CR2–3 chondrites, indicating that QUE 99038 is spectrally and mineralogically distinct from CM2 and CR2–3 chondrites. It again resembles the CO3 chondrite ALH 77003 in the 1 μm region, but, as mentioned, differs in the 2 μm region.

4.12. Tagish Lake (C2-unique; affinities to CM2, CR2, CI1)

4.12.1. Description
The Tagish Lake carbonaceous chondrite, which fell in 2000 (Brown et al., 2000), was recognized as a new type of CC almost immediately. It has at least four distinct lithologies: carbonate-poor, carbonate-rich, inclusion-poor magnetite- and sulfide-rich, and carbonate-rich, siderite-dominated (Bland et al., 2002; Zolensky et al., 2002; Izawa et al., 2010). Modal mineralogies for a number of subsamples are given in Tables 3 and 4. Overall, Tagish Lake is composed of abundant phyllosilicate-rich matrix (~80%), and lesser amounts of carbonates, olivine, sulfides, and magnetite, sparse CAIs, and aqueously-altered chondrites (Alexander et al., 2007).

The carbonate-poor lithology consists of fine- to coarse-grained, phyllosilicate-rich clasts, sparse altered chondrules, aggregates, sparse CAIs, grains of olivine, magnetite, Fe–Ni sulfides, phosphides, and rare carbonates (Zolensky et al., 2002). The carbonate-rich lithology is more depleted in CAIs, aggregates, fine-grained sulfides, and magnetite, the phyllosilicates are almost entirely saponite, and Fe–Mg–Ca–Mn carbonates are very abundant (Zolensky et al., 2002). Noguchi et al. (2002) described the two major lithologies as follows: the carbonate-rich matrix contains saponite, pyrrhotite, Mg-siderite, pentlandite, and magnetite, and the carbonate-poor matrix contains saponite, magnetite, pyrrhotite, Mg-siderite, pentlandite, and calcite. Gypsum and talc have been found in inclusion-rich subsamples of Tagish Lake (Izawa et al., 2010).

4.12.2. Matrix and phyllosilicates
The matrix consists of intergrown saponite and serpentine, Mg–Fe carbonates, Fe–Ni sulfides (mostly pyrrhotite); magnetite and olivine are also present (Brown et al., 2000; Keller and Flynn, 2001; Noguchi et al., 2001; Zolensky et al., 2002; Bland et al., 2004). The phyllosilicates are compositionally similar to Ivuna (CI1) and more Fe-rich than Orgueil and Alais (CI1) (Keller and Flynn, 2001). The phyllosilicates are Fe/(Fe + Mg) ~ 0.3 (Zolensky et al., 2002).

<table>
<thead>
<tr>
<th>Table 3 Modal mineralogy of the Tagish Lake carbonaceous chondrite. Source: Bland et al. (2004).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
</tr>
<tr>
<td>Olivine (Fo100)</td>
</tr>
<tr>
<td>Fe–Mg carbonate</td>
</tr>
<tr>
<td>Pyrrhotite</td>
</tr>
<tr>
<td>Pentlandite</td>
</tr>
<tr>
<td>Magnetite</td>
</tr>
<tr>
<td>Saponite–serpentine</td>
</tr>
</tbody>
</table>
The organic matter is closely associated with the phyllosilicates (Pearson et al., 2002; Garvie and Buseck, 2004). Total carbon content has been measured as 4.25 wt.% (Pearson et al., 2006), or 5.4 wt.%, with an estimated 0.79% (Cody et al., 2003). Organic C content is 2.00 wt.% (Alexander et al., 2010) consisting of a few (10%) rings in a disordered arrangement (Derenne et al., 2006), and are highly condensed (Gilmour et al., 2001). The insoluble organic matter has the highest aromaticity and lowest bulk H/C ratio of any petrologic type 1–2 CC (Alexander et al., 2010). The fraction of aromatic carbon is 0.79% (Cody et al., 2003). Organic C content is 2.00 wt.% (Alexander et al., 2007). There are wide variations in many organic component properties between different lithologies of Tagish Lake that provide insights into differences in parent body processing (Herd et al., 2010).

4.12.4. Carbonates

A variety of carbonates seem to exist in Tagish Lake, with relative abundances varying between the major lithologies. Different samples can contain Fe- and Ca-rich carbonates or just Fe-rich carbonates (Blinova and Herd, 2010; Izawa et al., 2010). Brown et al. (2000) describe the carbonates as varying between siderite, magnesium, and calcite, with some containing up to 1% Mn. Dolomite is the major carbonate in altered chondrules (Zolensky et al., 2002). Calcium carbonate is the most common carbonate in the carbonate-poor lithology (Zolensky et al., 2002), but uncommon compared to the carbonate-rich lithology, and it can contain some Fe. According to Zolensky et al. (2002), Fe-Mg–Ca–Mn carbonates are very common in the carbonate-rich lithology, but calcium carbonate grains are rare, while the carbonates in the carbonate-rich lithology seem to consist of calcium carbonate cores with Mg–Fe–Mn carbonate rims. Changes in carbonate mineralogy are indicative of differences in degree of aqueous alteration (Rubin et al., 2007).

4.12.5. Classification and comparison to other CCs

Abundant phyllosilicates, sparse chondrules and common olivine inclusions in the matrix are consistent with petagetic grade 2 (Gounelle et al., 2001). Tagish Lake has a matrix mineralogy similar to CR2 chondrites (Gounelle et al., 2001), while the presence of altered chondrules and CAIs, olivine composition, and relative abundance of sulfides are consistent with CM2 chondrites (Gounelle et al., 2001; Rubin et al., 2007). Isolated, unaltered olivine grains and the anhydrous inclusions share similarities with CM meteorites, but Tagish Lake has been more extensively aqueously altered than known CM chondrites (Simon and Grossman, 2003; Rubin et al., 2007).

4.12.6. Reflectance spectra

A number of Tagish Lake samples have been spectrally characterized (Hiroi et al., 2001a,b, 2003, 2004). Hiroi et al. (2001a) found a close spectral similarity to D asteroids, specifically 368 Haidea (Hiroi et al., 2001a,b), and to other T- and D-class asteroids (Hiroi et al., 2003). Spectra of Tagish Lake available for analysis, including fresher (ET01b) and more weathered (PM05c) samples (Hiroi et al., 2001b). Fig. 13a shows that <125 μm powder spectra of these two subsamples are very similar. A pressed powder has higher reflectance and is less red-sloped than loose powders. While the spectra may appear featureless, continuum removal in the 0.6–0.8 and 0.8–1.5 μm region shows the presence of shallow (~1–2% deep) absorption features (Fig. 13b). A ~1% deep band is located at 0.7 μm, and is attributable to Fe3+/Fe2+ charge transfers in the abundant Fe-bearing serpentine; this phase also likely accounts for the bands near 0.9 and 1.1 μm. These bands resemble those seen in other serpentine-bearing CCs, such as CMs (Cloutis et al., 2011b), but much suppressed. There are suggestions of contributions by olivine near 1.25 μm, although this feature is not well expressed; olivine is present but sparse in Tagish Lake. The overall reflectance of Tagish Lake is low, ~2% at 0.56 μm, lower than the values for CMs (Cloutis et al., 2011b), and consistent with the organic matter being intimately associated with the phyllosilicates (Pearson et al., 2002; Garvie and Buseck, 2004). Rouš (2003) found that a number of phases in this meteorite contribute to its spectrum. Possible contributions from the various carbonates and/or serpentine in Tagish Lake are suggested by the weak, broad absorption feature seen in the 2.3–2.4 μm region of the loose powder spectra.

The red-sloped, nearly featureless spectrum of Tagish Lake is unique among carbonaceous chondrites. It probably arises from the highly aromatic nature of the organic component, and its intimate association with the phyllosilicate-rich matrix, which makes up a high proportion of this meteorite, probably accounts for its spectral characteristics (Cloutis, 2003).

5. Discussion

The most fruitful approach to analysis of ungrouped/unassigned CCs relies largely on analysis of spectrally active phases – i.e., those phases that contribute absorption features to the CC spectra. We can use the presence or absence of features, coupled to their approximate wavelength positions as diagnostic determinations of CC mineralogy. We also include properties such as shape of absorption features (indicative of possible overlapping or multiple bands), band depths, albedo, and spectral slope in the analysis. These are generally less useful than the mere presence of absorption bands because
Fe\textsuperscript{3+}–Fe\textsuperscript{2+} intervalence charge transfers in serpentine appear, while in the M2 site (Burns, 1970), and the 1.05 and 1.25 \textmu m (Cloutis et al., 2012b), and as a result, the presence of serpentine can usually be discerned from absorption bands in the 0.7, 0.9, and 1.1 \textmu m regions. In rare instances, the presence of serpentine can be verified by an absorption band, invariably weak, at 2.32 \textmu m. Carbonates, which are abundant in Tagish Lake (Tables 3 and 4) could also give rise to an absorption feature in the 2.3 \textmu m region, which is also normally weak.

The 2 \textmu m region is where absorption bands due to crystal field transitions in Fe\textsuperscript{2+} located in the M2 site of pyroxene can also appear. In contrast to the 1 \textmu m region, the 2 \textmu m region is not interfered by olivine or serpentine, and reflectance is often higher in this region, making it more suitable for determining the presence of pyroxene (e.g., Coolidge, DaG 430, MET 01149, QUE 99038). The position of this band can be used to constrain pyroxene chemistry (Cloutis and Gaffey, 1991). The 2 \textmu m region is also where Fe\textsuperscript{2+}-bearing spinels exhibit an absorption band (Cloutis et al., 2004). Tetrahedrally coordinated spinel Fe\textsuperscript{2+} is an intense absorber, so small amounts of such a spinel can give rise to a detectable absorption band. Such a feature is common in CO and CV spectra (Cloutis et al., 2012c,d). Determining the presence of pyroxene and/or spinel can be complicated by a number of factors. The presence of a water band near 1.9 \textmu m can mask a weak pyroxene band, and the spinel absorption band is broad and can overlap the pyroxene band. However, in general, an absorption band centered shortward of 2 \textmu m is characteristic of low-Ca pyroxene, while a band longward of 2 \textmu m is more characteristic of Fe\textsuperscript{2+}-bearing spinel. The presence of spinel can best be determined by a 2 \textmu m region absorption feature with a suppressed long wavelength reflectance increase.

The presence of fine-grained opaque phases causes a reduction in albedo and mafic silicate absorption bands. As evidenced from the Coolidge and Tagish Lake spectra, opaques can induce overall slopes that range from blue to red. Metal and sulfides will introduce an overall red slope (Britt and Pieters, 1988; Britt et al., 1992). Thus, a red slope does not necessarily imply organics or metal, but a blue slope strongly implies organics; there is also some evidence that fine-grained magnetite may be able to produce a modest blue slope (Cloutis et al., 2011b). Slope changes and reductions in albedo are also possible by changes in grain size. Johnson and Fanale (1973) demonstrated that with increasing grain size (and removal of the finest fraction), CC spectra become bluer and darker. This further complicates assigning a unique mechanism to the slopes of CC spectra. Albedo has been shown to be a useful criterion for assessing some of the CCs in this study, which may have albedos that are higher or lower than the range seen in CC groups for comparably sized fractions. The analysis of Coolidge and CR chondrites: Cloutis et al., 2012a) also suggests that Fe oxyhydroxides produced during terrestrial weathering can significantly alter CC spectra, particularly those containing low Fe content mafic silicates.
One factor that has emerged from this study is that even abundant fine-grained, dispersed opaques present at the levels seen in CCs are unable to fully suppress mafic silicate absorption bands. Tagish Lake is a prime example of this – mafic silicate bands persist in its spectra, albeit with depths on the order of 1%. Highly suppressed mafic silicate absorption bands are also seen in CCs with Fe-poor silicates (e.g., Cloutis et al., 2012a).

### 5.1. Characterizing ungrouped and poorly-characterized CCs

Assigning or characterizing ungrouped or poorly-characterized meteorites should rely on multiple factors. We have found that all of the CCs and R chondrites included in this study exhibit absorption features that can be related to various mineral phases that they contain (e.g., olivine, Fe$^{2+}$ and Fe$^{3+}$, Fe$^{3+}$-bearing serpentine, pyroxene, spinel, Fe$^{3+}$ oxyhydroxides). By determining which phases are present, combined with band depth and albedo information, reasonable inferences can be made concerning their affinities to specific CC groups. We have found that absorption band positions, which are useful for characterizing the composition of single minerals in the laboratory, are not as useful for determining mineral compositions of CCs. The shapes of absorption features do have some usefulness, particularly for assessing the presence of multiple phases in a spectrum, but again, it appears that only broad constraints can be placed on end member abundances.

While some CC groups are discriminated more on textural than compositional criteria (e.g., CO versus CV chondrites), powdered CCs will not preserve any useful textural information. We expect asteroid surfaces to be similarly devoid of textural information, and as a result, we focused our analysis of CCs on compositional criteria. As mentioned above, we also base our analysis on petrologic properties that are most robustly preserved in CC spectra. Even with these limitations, we have found that the spectra of the “orphan” CCs included in this study can be characterized to a sufficient level of detail to make reasonable inferences concerning their uniqueness or inclusion in established groups.

### 6. Summary

Our analysis of the reflectance spectra of a number of CCs and R chondrites has provided useful insights into the degree to which spectral analysis can be used for characterization, the spectral features that can be used for such characterization, and their limitations. As mentioned above, mafic silicate absorption features are ubiquitous in the CCs and R chondrites we have examined. Combining information on these features along with albedo and spectral slopes allows reasonable inferences to be made concerning their uniqueness. To recap the major results of this work:

- Reflectance spectra of Coolidge show contributions from olivine, and Fe oxyhydroxides produced during terrestrial weathering, and its high reflectance and mafic silicate band depths are consistent with a petrologic grade $>$3 and inconsistent with CV chondrites.
- The nature of the Cumberland Falls inclusions from spectral analysis is inconclusive, but they do exhibit spectral features consistent with their overall mineralogy.
- The spectrum of DaG 430, which shares characteristics of both CV and CK chondrites, is not fully consistent with either group.
- The spectrum of EET 96029 is consistent with some CM2 chondrites.
- GRO 95566, a meteorite with some affinities to CM2s, most resembles the Renazzo CR2 chondrite, consistent with their similar mineralogies. The CR group is very diverse and its limits are not well defined (Weisberg et al., 1993, 1995). The spectral properties of GRO 95566 can be related to its major mineralogic characteristics.
- The spectra of Kaidun are most consistent with CR chondrites. CR material forms the bulk of this complex polymict breccia, suggesting that the samples of Kaidun that were spectrally characterized did not include substantial amounts of non-CR lithologies. Spectra of larger grain sizes are more useful for assessing the nature of mineral components in this meteorite.
- The reflectance spectrum of MCY 92005 is consistent with its recent classification as a CM2 chondrite.
- The R3 chondrite MET 01149 has a spectrum consistent with its low abundance of opaques and Fe-rich silicates.
- The combination of high reflectance, deep 1 μm band and, to a lesser extent, slightly red slope and weak 2 μm region absorption band, distinguishes PRE 95404 from CV3s, to which it was initially assigned.
- LAP 04840 has a spectrum dominated by olivine, consistent with an R chondrite of petrologic grade $>$3. Its reflectance is somewhat lower than for the R3 chondrites, and falls within the range of many CCs. Its most characteristic feature is the metal–OH absorption feature in the 2.3 μm region.
- Analysis and assignment of PCA 91467 (CH3) is complicated by the presence of weathering products (Fe oxyhydroxides) which strongly affect its weak mafic silicate absorption bands; this is an issue also encountered in our analysis of CR chondrites (Cloutis et al., 2012a). The red slope of this meteorite is consistent with its high metal content, but may also be affected by Fe oxyhydroxides. Its overall reflectance falls within the range for most CCs. Additional work on CH chondrites is required to better understand the spectral properties of this group.
- Reflectance spectra of the howardite PRA 04401, which contains ~40% CM2-like inclusions, is dominated by the howardite’s pyroxene absorption bands. Expected CM2 type absorption bands, near 0.7, and 1.1 μm are not seen and this may be due to their absence or dominance by the pyroxene. The CC xenoliths do lower overall reflectance and pyroxene absorption band depths significantly, and probably add an overall red slope as compared to inclusion-free howardites.
- QUE 99038, which has been linked to CM2, CO, or CR chondrites is not consistent with any of these groups. The 2 μm band, high overall reflectance, and dominant olivine absorption band are all generally inconsistent with CM2 and CR2–3 chondrites. It resembles the CO3 chondrite ALH 77003 in the 1 μm region, but differs in the 2 μm region.
- The red-sloped, nearly featureless spectrum of Tagish Lake is unique among carbonaceous chondrites. It probably arises from the highly aromatic nature of the organic component and its intimate association with the phyllosilicate-rich matrix. The matrix, which makes up the bulk of this meteorite, probably accounts for its spectral characteristics.

### 7. Conclusions

The spectral properties of the major CC groups are well enough known and relatable to their mineralogies that ungrouped or new meteorites can be compared to them with some level of confidence for determining group membership or uniqueness. As more members of CC groups are spectrally characterized, the limits of their spectral variability will become better defined. However, our knowledge of the causes of spectral similarities and differences within and between groups and individual meteorites is hampered by a number of factors. These include incomplete knowledge of the ways in which the composition and physical disposition of opaque minerals affect CC reflectance spectra. In addition, how much terrestrial weathering has affected CC spectra is not well constrained
in many cases. Some of these issues can be overcome by the application of optical models and more laboratory studies of the spectral properties of mixtures involving fine-grained opaques. Finally, as new CCs are identified, and membership in existing groups expands (perhaps with different petrologic grades), the spectral and compositional boundaries between groups will blur, making characterization of new meteorites more difficult.

In terms of identifying CC parent bodies, our understanding of how space weathering and exposure of asteroid surfaces to the vacuum of space affects them needs to be further developed. Combining thermal infrared with reflectance spectra can also aid in better constraining asteroid surface compositions. Finally, our knowledge of the physical properties of asteroid surfaces must be improved. The common approach of using comminuted CCs to compare with asteroid surfaces may not be valid in all cases, and needs to be verified.

Acknowledgments

We wish to thank the invaluable and generous assistance provided by many individuals which made this study possible. In particular we thank the US and Japanese Antarctic meteorite programs for recovering many of the samples included in this study. We also wish to thank Dr. Andreas Nathues from the Max Planck Institute for providing samples of PRA 04401 and a number of other howardites, Mike Zolensky and Andrei Ivanov for the sample of Kaidun, and Katsuhiro Ohtsuka for DaG 430. The RELAB facility at Brown University is a multi-user facility operated with support from NASA Planetary Geology and Geophysics Grant NNG06GJ31G, whose support is gratefully acknowledged. This study was supported by a NSERC Discovery grant to WC. We also wish to thank Josep Trigo-Rodriguez and an anonymous reviewer for their valuable and thoughtful comments and suggestions.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2012.10.008.

References


