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1 Visible-Infrared spectroscopy of ungrouped and rare meteorites brings further constraints on
2 meteorite-asteroid connections.

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12

13 **Abstract**

14 The composition of asteroids gives crucial insights into the formation and evolution of the Solar
15 System. Although spectral surveys and spacecraft missions provide information on small bodies,
16 many important analyses can only be performed in terrestrial laboratories. Meteorites represent our
17 main source of samples of extraterrestrial material. Determining the source asteroids of these
18 meteorites is crucial to interpret their analyses in the broader context of the inner Solar System. For
19 now, the total number of parent bodies represented in our meteorites collection is estimated to about
20 150 parent bodies, of which 50 parent bodies represented by the poorly studied ungrouped
21 chondrites. Linking ungrouped meteorites to their parent bodies is thus crucial to significantly
22 increase our knowledge of asteroids. To this end, the petrography of 25 ungrouped chondrites and
23 rare meteorite groups was studied, allowing grouping into 6 petrographic groups based on texture,
24 mineralogy, and aqueous and thermal parent body processing. Then, we acquired visible-near-
25 infrared (VIS-NIR) reflectance spectroscopy data of those 25 meteorites, in order to compare them
26 to ground-based telescopic observations of asteroids. The reflectance spectra of meteorites were
27 obtained on powdered samples, as usually done for such studies, but also on raw samples and
28 polished sections. With asteroids surfaces being more complex than fine-grained regolith (e.g.,
29 asteroid (101955) Bennu), in particular near-Earth asteroids, the use of raw samples is a necessary
30 addition for investigating parent bodies. Our results showed that sample preparation influences the
31 shape of the spectra, and thus asteroid spectral matching, especially for carbonaceous chondrites.
32 Overall, the petrographic groups defined initially coincide with reflectance spectral groups, with
33 only few exceptions. The meteorite spectra were then compared with reference end-member
34 spectra of asteroids taxonomy. We matched the 25 studied meteorites to asteroids types, using a
35 qualitative match of the shape of the spectra, as well as a quantitative comparison of spectral
36 parameters (bands positions, bands depths and slopes at 1 and 2 μm). We define links between

37 some of the studied ungrouped chondrites and asteroid types that had no meteorite connection
38 proposed before, such as some very primitive type 3.00 ungrouped chondrites to B-type or Cg-type
39 asteroids. We also matched metamorphosed ungrouped carbonaceous chondrites to S-complex
40 asteroids, suggesting that this complex is not only composed of ordinary chondrites or primitive
41 achondrites, as previously established, but may also host carbonaceous chondrites. Conversely,
42 some ungrouped chondrites could not be matched to any known asteroid type, showing that those
43 are potential samples from yet unidentified asteroid types.

44 1 Introduction

45 The knowledge of the spatial distribution and composition of Solar System small bodies (asteroids,
46 Trojans, trans-Neptunian objects (TNOs) and comets) gives us insight into the formation and
47 dynamical evolution of the Solar System. The composition of small bodies is mainly known from
48 the analysis of the sunlight reflected from their surfaces. Indeed, the major minerals composing
49 asteroids (silicates) have specific absorption bands in the visible (VIS) and Near Infrared (NIR)
50 wavelengths. Spectral surveys have measured the reflectance of asteroids in the visible range of
51 wavelengths ($\sim 0.4\text{-}1.1\ \mu\text{m}$) (e.g. Tholen, 1984; Zellner et al., 1985; Bus, 1999; Lazzaro et al., 2004)
52 and spectra up to $2.5\ \mu\text{m}$ are available for several hundreds of objects.

53 Using those spectra, asteroids have been grouped into different classes. The Tholen taxonomy
54 (1984), based on the Eight Color Asteroids Survey data (ECAS, Zellner et al., 1985), defined seven
55 major asteroid classes. Using the spectral diversity of the new CCD technology, Bus and Binzel
56 (2002) proposed an improved taxonomy with three major complexes (S, C and X), composed of
57 12 classes, including 26 different types of asteroids. Both the Tholen and Bus taxonomies are based
58 on Principal Component Analysis (PCA) of NIR spectral parameters. This taxonomy was then

59 revised by DeMeo et al. (2009) based on spectra up to 2.5 μm , eliminating three classes, creating
60 a new one, resulting in a total of 24 asteroid classes.

61 Spacecraft mission is another way to analyze asteroids, and collect information unobtainable from
62 Earth, such as spatially resolved reflectance spectra, high resolution image, bulk densities, and
63 magnetic field measurements. Those missions have so far visited only a dozen asteroids: (1) Ceres
64 and (4) Vesta (Dawn, Krohn et al., 2018), (253) Mathilde and (433) Eros (NEAR Shoemaker,
65 Prockter et al., 2002), (243) Ida and (951) Gaspra (Galileo, Johnson et al., 1992), (21) Lutetia and
66 (2867) Steins (Rosetta, Glassmeier et al., 2007), (4179) Toutatis (Chang'e 2, Huang et al., 2013),
67 (5535) Annefrank (Stardust, Duxbury et al., 2004), (9969) Braille (Deep Space 1, Buratti et al.,
68 2004), (25143) Itokawa (Hayabusa, Tsuda et al., 2013) and (486958) Arrokoth (New Horizons,
69 Young et al., 2008). During these missions, detailed elemental composition has only been obtained
70 for a few of these bodies ((1) Ceres, (4) Vesta, (433) Eros, (25143) Itokawa) (Burbine, 2016). A
71 third approach to study small bodies is through sample return missions. So far, one comet Wild 2
72 (Stardust mission) and two asteroids (25143) Itokawa (Hayabusa mission) and more recently
73 (132173) Ryugu (Hayabusa2 mission) have been successfully sampled. One additional sample
74 return mission, OSIRIX-Rex to asteroid (101955) Bennu is underway. The study of meteorites is
75 another method to study samples of small bodies. Meteorite collections contain over 60000
76 meteorites collected and catalogued since the early 1800's (see the Meteoritical Bulletin Database,
77 <https://www.lpi.usra.edu/meteor/>). Over 99.9% of those meteorites derive from asteroids, and only
78 a small fraction from planetary bodies such as Mars and the Moon (Burbine et al., 2002). For
79 chondrites, meteorites in the same group are thought to originate from the same primary parent
80 body (Greenwood et al., 2020). Achondrites' classification is different and not only based on their
81 parent bodies, but on petrography and chemistry, such that, for instance, meteorites originating
82 from asteroid Vesta are separated into three groups (Howardites, Eucrites, Diogenites). The current

83 classification comprises 50 groups of meteorites (Weisberg et al., 2006). In this study, we focus on
84 chondrites, that can be classified in 3 major classes: Ordinary (O), Carbonaceous (C) and Enstatites
85 (E); and 2 additional classes: Kakangari (K) and Rumuruti (R). Ordinary chondrites are the most
86 abundant meteorite type, subdivided in three groups, H, L and LL. The carbonaceous chondrites
87 are divided in several classes by petrographic and geochemical variations: CI, CM, CK, CV, CO,
88 CR, CB, and CH (Weisberg et al., 2006; Krot et al., 2014). However, these chondrites groups
89 represent only about half of the chondrite diversity. Indeed, some meteorites do not fit any of the
90 groups and are called “ungrouped”. Those ungrouped meteorites cannot be classified in one of the
91 main groups due to non-matching isotopic compositions, different petrographic characteristics,
92 and/or mineral compositions. According to the Meteoritical Bulletin database (accessed September
93 2020), most of the ungrouped chondrites are carbonaceous chondrites (55 of 86 ungrouped
94 chondrites). These meteorites have been classified as C2-ung and C3-ung meteorites, or just C2 or
95 C3 until recently. C2 and C3 designation should be exclusively reserved to meteorites whose
96 classification is not detailed enough to exclude affinities with a known chondrite group, but C2
97 chondrites, for example, comprises real ungrouped chondrites (C2-ung) but also many CM2
98 chondrites.

99 As a result, it is not straightforward to evaluate the number of ungrouped chondrites, and hence the
100 number of parent bodies that they sample. Based on oxygen isotopic composition considerations,
101 Greenwood et al. (2020) proposed that ungrouped chondrites originate from a maximum of 50
102 different parent bodies; ungrouped achondrites derived from 16 distinct parent bodies; and
103 ungrouped iron meteorites from a maximum of 50 parent bodies. Counting chondrites, achondrites
104 and ungrouped meteorites, the total number of parent bodies represented in our collection is thus
105 estimated to about 150 parent bodies (Gattacceca et al., 2020a). Based on oxygen isotopes studies,
106 Greenwood et al. 2020 estimated the number of different parent bodies to 95-148 asteroids, with

107 15-20 parent bodies for chondrites, and 11-17 parent bodies for ungrouped chondrites. Grouped
108 meteorites usually come from collisional families composed of multiple smaller objects, thus, our
109 sampling of asteroids may be biased toward family members (e.g. DeMeo et al., 2013; Vernazza
110 and Beck, 2016). Although meteorites are “float” rocks, i.e. collected outside of their geological
111 context, studying ungrouped meteorites may enable to sample rare asteroid types that possibly did
112 not produce collisional families.

113 Linking meteorites to asteroids is necessary to study the precise mineralogy of asteroids. The study
114 of chemical and isotopic compositions of asteroids, being building block of planet formation, allow
115 better understanding of composition and thermal gradients in the solar nebula. Manned space
116 missions may want to search asteroids for important resources relatively rare on Earth (Kargel,
117 1994). Also, near-Earth asteroids (NEAs) can strike the Earth and any deflection or destruction
118 strategy would need to include the mineralogy of those objects (Burbine et al., 2002).

119 A first approach to link meteorites to their origin in the Solar System is dynamical models, that
120 find that most meteorites originate from the inner main belt (e.g., Granvik and Brown, 2018). More
121 precisely, to link meteorites to their parent bodies is possible using automated camera networks
122 monitoring the sky for meteoroids. The goal of these networks is to find the heliocentric orbits of
123 meteoroids and ultimately their source regions in the Solar System (Granvik and Brown, 2018).
124 The use of these networks enabled to link only about 25 meteorites to their parent bodies (Granvik
125 and Brown, 2018).

126 The most used method to connect meteorite groups to parent bodies is finding spectral similarities
127 in the visible and near-infrared (NIR) (e.g. Thomas and Binzel, 2010; Burbine, 2016 and references
128 therein; Takir et al., 2019). Reflectance spectra of meteorites are measured in laboratory and
129 compared to asteroid reflectance spectra acquired through telescopes (Takir et al., 2019, Potin et

130 al., 2020). In addition, meteorites groups have distinctive spectra and absorptions in the spectral
131 range used for asteroids reflectance spectroscopy (0.3-2.5 μm) (Gaffey, 1976). The comparison
132 between meteorite and asteroid spectra is complicated as visible-near-infrared (VIS-NIR)
133 spectroscopy can be influenced by other factors than mineralogy, such as space weathering
134 (Chapman, 1996; Sasaki et al., 2001; Hapke, 2001), grain size (Johnson and Fanale, 1973),
135 temperature (Singer and Roush, 1985; Hinrichs et al., 1999) or adsorbed water (Beck et al., 2010;
136 Garenne et al., 2016; Takir et al., 2019). Despite these complications, links have been proposed
137 between some asteroid complexes and the main meteorites groups (see review Table 2 in
138 Greenwood et al., 2020), and most meteorites are linked to asteroids collisional families, such as
139 HEDs (howardites, eucrites, diogenites) to the Vesta family (DeMeo et al., 2013).

140 Although the spectral properties of the main meteorite groups have been studied in details (e.g.
141 Burbine et al., 2002; Beck et al., 2013; Burbine 2016; Vernazza et al., 2017; Takir et al., 2019;
142 Eschrig et al., 2020), the spectral properties of the ungrouped chondrites have received much less
143 attention, even though they represent a large fraction of the diversity of the meteoritic material
144 available for study. In addition, only a few studies have focused on connecting ungrouped
145 chondrites to asteroids. Indeed, Tagish Lake meteorite (C2-ung) was linked to either D- or T-type
146 asteroids by Hiroi et al. (2001) and Hiroi and Hasegawa (2003), and Izawa et al. (2015) linked the
147 meteorite to two NEAs ((326732) 2003 HB6 and (17274) 2000 LC16). Thus, the rest of the
148 ungrouped meteorites, which represent various meteorites mineralogies, and thus potential parent
149 bodies, are probable samples of other unlinked asteroids types.

150 In this paper, we study 25 meteorites (mostly chondrites), ungrouped or from rare groups, whose
151 spectral properties have never been studied or at least not in detail. First, we analyzed the
152 petrography of these meteorites to put some order in the hazy “ungrouped” designation. Then we

153 acquired Infrared (IR) reflectance data on these 25 meteorites and compared these results with
154 reference asteroids data. We discuss the limitations and parameters influencing the comparison of
155 asteroid to meteorite spectra, and propose possible connections between some of the studied
156 meteorites and potential asteroids parent bodies.

157 2 Samples and Methods

158 2.1 Samples

159 A suite of 25 meteorites was used in this study, with a focus on ungrouped chondrites. We studied
160 12 ungrouped chondrites, 2 anomalous chondrites and 11 meteorites from rare groups (Table 1).
161 The ungrouped meteorites comprise one ungrouped ordinary chondrite (JaH 846), one ungrouped
162 chondrite (Sierra Gorda 009), two ungrouped carbonaceous chondrites (Dhofar 2066 and North
163 West Africa (NWA) 8781), and three C2-ung chondrites (NWA 5958, Acfer 094 and El Médano
164 (EM) 100). We also studied three ungrouped carbonaceous chondrites of petrographic type 3.00
165 (Chwichiya 002, NWA 11750 and NWA 12957), the C3 chondrite El Médano (EM) 200, and
166 metamorphosed ungrouped chondrites with petrographic types ranging from type 3 to type 5/6 (Los
167 Vientos (LoV) 051, Sahara 00177, Coolidge, Mulga (West) by increasing order of thermal
168 metamorphism). The studied “grouped” meteorites were either from rare groups, with no parent
169 bodies associated yet (i.e., CH or Kakangari groups), or showed unusual petrographic features
170 making them anomalous in their group. They were also helpful to verify that the method used in
171 this paper gives results comparable to previous studies (Burbine et al., 2003; Dunn et al., 2010;
172 Moskovitz et al., 2010; Vernazza and Beck 2016; Vernazza et al., 2017; Lucas et al., 2019; Takir
173 et al., 2019). We selected five grouped carbonaceous chondrites: two CM chondrites, Aydar 003
174 (CM1/2) and NWA 11086 (CM-an), one CH3, Los Vientos (LoV) 200, and one CR3, NWA 12474.
175 We also studied the Kakangari meteorite, the only fall in the small K group, as well as two

176 Rumuruti chondrites: Awsserd (R4) and NWA 12472 (R3). We also analyzed the ordinary
177 chondrite NWA 12334 (LL6-an). Finally, two primitive achondrites, NWA 6592 (Iodranite) and
178 NWA 12480 (Acapulcoite), were added to complete the variety of studied samples.

179 The surface of asteroids can be made of dust, regolith, or boulders. For better comparison to these
180 blocky and/or dusty surfaces, we measured raw and powdered samples for each meteorite. For
181 powdered samples, we used around 200 mg of material, dry ground in an agate mortar, giving a
182 grain size $< 100 \mu\text{m}$. Polished sections were used as a substitute for raw samples in the case where
183 samples were only available in that form. The comparison between the spectra of the different types
184 of samples will be discussed in this paper. Most studied samples were analyzed using the three
185 samples preparation (raw, powdered and polished samples).

186 **2.2 Petrography**

187 Polished sections of all meteorites were observed with a Leica DM2500P petrographic microscope.
188 Observations and maps were made using reflected light on thick polished sections. Modal
189 abundances of chondrites components (chondrules, matrix, opaques) were evaluated by point
190 counting, with 95% confidence interval around the modal abundance computed after Howarth
191 (1998). Chondrule sizes were measured by contouring chondrules outlines on optical maps using
192 the *Photoshop* software, followed by image analysis using the *ImageJ* software.

193 Backscattered Secondary Electron (BSE) images were taken on all meteorites. Chemical
194 compositions were evaluated by Energy Dispersive Spectrometry (EDS) analyses. Both BSE and
195 EDS analyses were obtained with a Hitachi S3000-N SEM equipped with a Bruker X-ray EDS at
196 the Centre Européen de Recherche et d'Enseignement en Géoscience de l'Environnement
197 (CEREGE).

198 Petrophysical parameters (magnetic properties) were also used for a better characterization of the
199 studied meteorites. Magnetic susceptibility was measured with a MFK1 or KLY2 instruments
200 depending on sample size. Saturation magnetization was determined from hysteresis loops
201 measured with a Princeton model 2900 Micromag vibrating sample magnetometer (see Gattacceca
202 et al., 2014 for a comprehensive description). All magnetic measurements were also performed at
203 CEREGE.

204 **2.3 Reflectance Infrared spectroscopy**

205 **2.3.1 Instrumentation**

206 The Infrared (IR) spectroscopy analyses were performed at the Institut de Planétologie et
207 d'Astrophysique de Grenoble (IPAG) using the SHADOWS instrument (Potin et al., 2018). We
208 measured reflectance spectra under nadir incidence and with an observation angle of 30°. The
209 instrument was used in a standard mode, enabling a spot size of about 5.2 mm in diameter. All
210 spectra were normalized to infragoldTM and spectralonTM. For each sample, we measured the
211 reflectance spectra in a range from 0.3 μm to 2.6 μm , with a step of 20 nm.

212 **2.3.2 Terrestrial weathering**

213 Terrestrial weathering of the meteorites can also influence the spectra and thus the comparison of
214 meteorite and asteroid spectra. Typical terrestrial weathering products, iron oxides/hydroxides,
215 generally exhibit absorption edges around 0.55-0.60 μm , with absorption bands at 0.5 and 0.9 μm
216 and weaker absorption associated to OH- observable at 1.4 and 1.9 μm (Hiroi et al., 1993; Cloutis
217 et al., 2010). As this weathering is only terrestrial, those products should be removed to improve
218 the comparison of meteorite and asteroids infrared spectra. To reduce the effect of terrestrial
219 weathering on meteorite spectra and ease the comparison with asteroid spectra, strongly weathered
220 samples were treated with a leaching process (Cornish and Doyle, 1984; Lucas et al., 2019). Lucas

221 et al. (2019) showed that EATG leaching treatment did not affect the silicates bands positions, and
222 slightly increases the depths of the bands on the reflection spectra on anhydrous meteorites and
223 pyroxene and olivine control samples. In this paper, we tested different leaching processes in order
224 to choose the most efficient and least aggressive on carbonaceous chondrite samples (HCl, EATG
225 and HCl+ EATG). We measured spectra from 0.35 to 4 μm to observe the effect on silicates as
226 well as on hydrated minerals bands. We compared the spectra without leaching to the spectra for
227 the three types of leaching. We observed the same silicates bands positions with a small increase
228 in the depth of the silicate's bands. We also observed that the 3 μm band of hydrated minerals was
229 not significantly modified by the leaching. Thus, we chose to follow the same methodology as
230 Lucas et al. (2019) as it did not show any strong effect on the studied hydrated chondrites except
231 for the removal of terrestrial alteration. We used around 200 mg of powdered samples left in 5 mL
232 Ethanolamine Thioglycolate (EATG) 67% in Thioglycolate acid (TGS) 40% for 2 hours. After two
233 to three EATG cycles for the most weathered samples, the samples were thoroughly rinsed with
234 water first, then pure IPA before being dried.

235 **2.3.3 Separation of asteroids complexes and types**

236 The comparison of asteroid spectra to meteorite spectra is limited by the resemblance of some
237 asteroid complexes in reflectance spectra in the studied wavelength range. Especially, some
238 meteorites, such as Chwichiya 002 or NWA 11750, could be linked to both X- and C-complex
239 asteroids. Indeed, the types Cg, Cgh, Ch, Xk, Xc and Xe are not easily separated on component
240 space methodology used by DeMeo et al. (2009), because their spectral features are weak. The
241 study made in this paper is made at the first order, with spectral shape and parameters comparison,
242 so the differentiation of the match of the two complexes of asteroids is not possible for all
243 meteorites.

244 In greater details, some asteroid spectra of the same complex were too similar to be differentiated
245 during the process of matching the spectra of meteorites to asteroids. Indeed, for some asteroids,
246 the difference between two asteroid spectra is smaller than the difference to the closest matching
247 meteorite. For example, Xe- or Xk-type asteroid spectra are very similar, so they will often be
248 matched to the same meteorite. DeMeo et al. (2009) show that Xe- and Xk- type spectra are very
249 similar and need the detailed study of a slight feature around 0.9-1 μm to differentiate the two
250 types. In our study, we did not try to differentiate the two spectra, so they are both matched with
251 the same meteorites.

252 Another limitation of the comparison of asteroids to meteorites is the complexity of the mineral
253 composition of asteroids surfaces. An asteroid could be composed of different chondrite types, thus
254 the spectra obtained from this asteroid corresponds to the average of the different type of
255 mineralogy composing its surface. It could therefore be an average spectrum of different meteorite
256 spectra. In consequence, the comparison of one asteroid spectrum to one meteorite spectrum is
257 limited, as both scales are very different. For example, laboratory measurements of hydrated
258 carbonaceous chondrites show band depths stronger than the associated Cg- and Cgh-type
259 asteroids. If we rule out space weathering effects, it could be explained by the surface of the
260 asteroids being made of both hydrated and non-hydrated carbonaceous chondrites (Beck et al.,
261 2018).

262 **2.3.4 Space weathering**

263 It is also discussed that optical properties of the surface of an asteroid can change with processes
264 such as micrometeorite impact and sputtering due to solar wind (e.g., Chapman, 1996; Sasaki et
265 al., 2001; Hapke, 2001). Those processes can influence the spectra of the asteroids and create
266 differences between asteroid and meteorite spectra. Indeed, this process is understood between S-
267 type asteroids and their linked ordinary chondrites (Sasaki et al., 2001, Strazzulla et al., 2005,

268 Marchi et al., 2005, Brunetto et al., 2006, Vernazza et al., 2009a). It could therefore also influence
269 the matching of ungrouped meteorites with other asteroids types. In the case of silicate-rich
270 asteroids, space weathering reduces silicates bands depths, and increases the slopes of the VIS-NIR
271 spectra. In the case of carbonaceous asteroids, space-weathering effects are likely present, and
272 would have similar effect, but of lower magnitude (Lantz et al., 2017; Rubino et al., 2020). We
273 also believe that space weathering is stronger on the asteroids than on the meteorite samples studied
274 on earth. Space weathering effects are located at the very surface of the samples, i.e. the first
275 micrometer. Since the samples studied here are meteorites, the atmospheric entry did erase any
276 fingerprints of space weathering by meteor ablation and production of a fusion crust. Thus, the
277 asteroid spectra could have a redder VIS-NIR slope and show shallower absorption bands than the
278 associated meteorite. Since this effect is hardly quantifiable on the asteroid's spectra, to ease the
279 comparison of meteorites and asteroids, we chose to make the hypothesis that asteroids have low
280 space weathering.

281 **2.4 Spectral parameters and establishment of methodology**

282 To analyze the reflectance spectra, a set of well-defined spectral features was determined to allow
283 for meteorite-meteorite and meteorite-asteroid comparisons. This was done as described in Eschrig
284 et al. (2020) which follows earlier works by Cloutis et al. (2012). The spectral features include
285 several spectral band depths, positions and slopes which were consistently determined using a
286 python script. The 1 μm and 2 μm band ranges were fit with baselines by determining the maxima
287 on either side of the bands. Subsequently, the 1 μm and 2 μm slopes (nm^{-1}), band depths (%) and
288 positions (nm) were determined. The slopes were taken from the 1 μm and 2 μm band baseline
289 slopes and the band depths and positions were determined following Clark et al. (1999). In case of

290 spectra with particular shapes, the positions of the margins of the baseline were adapted manually
291 as seen fit by the author, using spectra shapes, silicates bands positions and slopes changes.

292 3 Petrography

293 In order to introduce some logic in the population of studied meteorites, we grouped them into six
294 meaningful petrographic groups, labelled A to F in the following (Table 1). The key petrographic
295 features are summarized in Table 1, and BSE images are provided in Figures 1 to 5. Two magnetic
296 parameters (saturation magnetization, M_s , and magnetic susceptibility, $\log\chi$, with χ in $10^{-9} \text{ m}^3/\text{kg}$),
297 which are quantitative proxies to the abundance of ferromagnetic minerals (mostly metal and/or
298 magnetite in the studied meteorites), are also given in Table 1. It is noteworthy that these are two
299 intrinsic magnetic parameters that cannot be affected by exposure to magnetic fields (such as
300 magnets). However, for metal-bearing meteorites, they decrease with increasing terrestrial
301 weathering due to the progressive destruction of metal (e.g., Rochette et al., 2003). The
302 petrographic group A (Fig. 1) comprises ungrouped carbonaceous chondrites that do not show
303 evidence of significant thermal metamorphism nor aqueous alteration: Chwichiya 002, NWA
304 11750, NWA 12957, and Acfer 094. Chwichiya 002, NWA 11750, and NWA 12957 show roughly
305 similar petrography indicative of very low or absent aqueous alteration and absence of significant
306 thermal metamorphism, based on Raman spectroscopy, X-Ray Diffraction (XRD) and Infrared (IR)
307 transmission spectroscopy, thus their petrographic type 3.00. They show broadly CM-like
308 petrography, with high matrix abundance (63.3-74.0 vol%), low chondrule abundance (12.9-26.0
309 vol%), and small chondrule apparent diameter (average in the range 240-480 μm) (Table 1), but
310 they differ from CM chondrites in their oxygen isotopic compositions and no evidence for
311 significant aqueous alteration (Gattacceca et al., 2020b). Acfer 094 is classified as C2-ung, with
312 trace element and petrography resembling CM2 chondrites. However, it is pooled here with C3.00

313 chondrites because XRD does not evidence a significant amount of phyllosilicates, and Acfer 094
314 contains more pre-solar SiC grains (very sensitive to aqueous alteration and thermal
315 metamorphism) than any other meteorite, suggesting minimal thermal or aqueous processing
316 (Newton et al, 1995). It shows a slightly different silicate composition, with addition of plagioclase
317 compared to the other 3 meteorites from this group A, and a slightly lower matrix abundance (60.9
318 vol%).

319 The petrographic group B (Fig. 2) is composed of CM-like meteorites, similar to the group A, but
320 with meteorites showing significant traces of aqueous alteration. This group comprises Aydar 003
321 (CM1/2), NWA 11086 (CM-an), El Médano (EM) 100 (C2-ung), NWA 8781 (C-ung), NWA 5958
322 (C2-ung), and EM 200 (C3). Aydar 003 (CM1/2) shows small chondrules, mineral fragments,
323 Calcium–aluminum-rich inclusion (CAIs), sulfides, and magnetite in an abundant fine-grained
324 phyllosilicate-rich matrix, like CM chondrites (Gattacceca et al., 2020c). NWA 11086 (CM-an)
325 also has a petrography resembling CM2 chondrites. It shows no phyllosilicates by XRD, but VIS-
326 NIR reflectance spectra (see below) reveal the presence of a low amounts of phyllosilicates
327 (Gattacceca et al., 2019). NWA 5958 (C2-ung) has affinities with CM2 chondrites but with oxygen
328 isotopes composition plotting on an extension of the carbonaceous chondrites anhydrous minerals
329 mixing line (CCAM) (Jacquet et al., 2016). EM 100 (C2-ung) also resembles CM2 chondrites but
330 has unusual oxygen isotopic compositions (Ruzicka et al., 2015). EM 200 (C3 with affinities with
331 CO3) shows no phyllosilicates by XRD, but small amounts of aqueous alteration on IR spectra of
332 the matrix (Ruzicka et al., 2015). NWA 8781 (C-ung) is a peculiar, it shows small chondrules,
333 absence of magnetite, unusual oxygen composition and absence of CAI. Phyllosilicate are not
334 found in the matrix, and ferroan olivine have 0.2-0.4 wt% Cr₂O₃ (Gattacceca et al., 2017) indicating
335 a subtype 3.0 (Brearley and Grossman, 2005).

336 The petrographic group C (Fig. 3) comprises ungrouped chondrites that show traces of aqueous
337 alteration, as previous group B, with the addition of small thermal metamorphism traces: NWA
338 12474 (CR3.1), Dho 2066 (C-ung), Kakangari (K); and chondrites with no matrix, LoV 200 (CH3),
339 and Sierra Gorda 009 (Chondrite-ung). NWA 12474 shows well-defined large chondrules with
340 composite opaque grains in an abundant fine-grained matrix, showing very slight metamorphism
341 and no phyllosilicates, based on Raman spectroscopy and XRD (Gattacceca et al., 2020c).
342 Kakangari has sharply defined chondrules surrounded by a high proportion of unequilibrated
343 matrix dominated by magnesian pyroxene (enstatite) and magnesian olivine, with few chondrules
344 (Weisberg et al., 1996; Barosh et al., 2020). It experienced secondary aqueous alteration and
345 metamorphism on its parent body (Barosh et al., 2020). The carbonaceous chondrite Dho 2066 has
346 been classified as C-ung but has been recently associated with the elusive CY group (Ikeda, 1992;
347 King et al., 2019). It has unusual oxygen isotopic composition and mineralogy (absence of
348 orthopyroxene, atypical olivine compositions compared to CMs), and low metal abundance (<1
349 vol%). It is probably paired with Dho 735, texturally resembling dehydrated CM2 chondrites, but
350 with different bulk chemistry and oxygen isotopic composition than CM2 chondrites (Ivanova et
351 al., 2010). LoV 200 (CH3) shows small packed chondrules, with almost no matrix, and abundant
352 metal.

353 Sierra Gorda 009 is somewhat intermediate between ordinary and enstatite chondrites. It resembles
354 “Low-FeO” or “G-chondrites” (Weisberg et al., 2015, Ivanova et al., 2020), with very high content
355 of metal, large pyroxene-rich chondrules and no fine-grained matrix. Its silicates are more reduced
356 than in H chondrites, but less reduced than in enstatite chondrites.

357 The petrographic group D is formed by two members of the relatively rare Rumuruti chondrites
358 group: Awsserd (R4) and NWA 12472 (R3) (Fig. 4a and Fig. 4b). Rumuruti chondrites show small
359 chondrules in an abundant matrix, with Fe-rich olivine as the main silicate and sulfides as the main

360 opaque phase (Fig. 4a and 4b). Both studied Rumuruti chondrites are significantly metamorphosed:
361 Awsserd has a petrographic type 4, and NWA 12472, based on the Cr₂O₃ content in the olivine of
362 0.13±0.05 wt.% (Gattacceca et al., 2020c) has an estimated subtype ≥3.2 (Brearley and Grossman,
363 2005).

364 The petrographic group E gathers significantly metamorphosed ungrouped chondrites (Fig. 4c to
365 4f). It contains Sahara 00177 (C3/4-ung), LoV 051 (C3-ung), Coolidge (C4-ung) and Jah 846
366 (OC3). Sah 00177, Coolidge and LoV 051 have relatively similar textures showing broad
367 similarities with the texture of reduced CV and CR chondrites (McSween and Richardson, 1977;
368 Ruzicka et al., 2017). However, they have higher metal/magnetite ratio than CVred chondrites,
369 lower matrix abundance than CVred and CR chondrites, and smaller chondrules than CVred and
370 CR chondrites (Metzler et al., 2020). JaH 846 has chondrules dominated by orthopyroxene and
371 silica polymorphs (Table 1) and an oxygen isotopic composition that is clearly separated from the
372 composition of the three groups of ordinary chondrites. The Cr₂O₃ content of its ferroan olivine
373 (0.08±0.06 wt%, n=8) indicate a petrographic type ≥3.2 (Gattacceca et al., 2020b)

374 Finally, petrographic group F gathers highly metamorphosed meteorites: NWA 12334 (LL6-an),
375 Mulga West (C5/6-ung), NWA 12480 (acapulcoite) and NWA 6592 (lodranite) (Fig. 5). The
376 metamorphosed anomalous ordinary chondrite NWA 12334 is an anomalous member of the LL
377 group. Compared to other LL chondrites, it has unusually high Fa content in olivine (Fa_{34.1±0.3}),
378 low magnetic susceptibility, and unusual opaque mineralogy featuring magnetite and pyrrhotite
379 instead of Fe,Ni metal (Gattacceca et al., 2020c). Mulga West shows a significantly recrystallized
380 CV-like petrography, with resorbed chondrules in an abundant fine granoblastic silicate matrix.
381 NWA 12480 shows a strongly recrystallized texture composed of mainly orthopyroxene (typical
382 size 400 μm), Ca-pyroxene, plagioclase (typical size 200 μm) displaying triple junctions

383 (McSween, 1977). Finally, NWA 6592 is composed of a coarse-grained of 1-2 mm mineral
384 aggregate of olivine, pyroxene, feldspar, and opaques, with texture showing triple junctions (Keil
385 et al., 2017).

386 4 Infrared spectroscopy

387 4.1 Infrared spectra of powdered samples

388 In this section we present the different spectra obtained by reflectance measurement on meteorite
389 powdered samples (Fig. 6). Spectra can be accessed in the SSHADE database at the following DOI:
390 https://doi.org/10.26302/SSHADE/EXPERIMENT_LB_20210201_001 (Krämer Ruggiu et al.,
391 2020). Spectral groups were made based on spectral similarities, in order to simplify the
392 comparison to asteroid spectra and interpretations (Table 2). In addition, to ease the comparison of
393 meteorite to asteroid spectra, we use the equivalent geometric albedo (Fig. 7). The equivalent
394 geometric albedo of the meteorites is obtained by using the reflectance value measured under
395 standard conditions (at 550 nm, a phase angle $g=30^\circ$) and multiplying by a factor from Figure 3 of
396 Beck et al. (2020), having the corresponding reflectance at very low angle ($g<2^\circ$). The main part
397 of the petrographic group (Fig. 1-5) mirrors the spectral grouping, except for a few meteorites
398 (Acfer 094, NWA 8781, JaH 846, and NWA 12334), showing that spectra features reflect mineral
399 abundances and compositions.

400 The first spectral group is composed of spectra showing no absorption bands, or very broad and
401 shallow absorptions around 1 μm only (Fig. 6a). They show a lack of 2 μm absorption bands, and
402 a flat spectral VIS-NIR slope. They also show low albedo at 550 nm typically ≤ 0.1 , except for EM
403 200 with an albedo slightly higher around 0.14 (Fig. 7). They all show a reflectance maximum
404 around 600 nm, with a small positive slope from 1 μm to higher wavelengths. The meteorites in
405 this spectral group are the NWA 11750, NWA 12957 and Chwichiya 002, all classified as C3.00-

406 ung. They correspond to the petrographic group A (Fig. 1), without Acfer 094, and with the addition
407 of EM 200 of petrographic group B.

408 We interpret these featureless spectra to reflect the high abundance of matrix (63.0, 73.4 and 74.0
409 vol%) rich in phases that show no spectral features (carbonaceous matter, opaques) (Table 1). The
410 lack of spectral features can also be explained by the low abundance of chondrules (12.9, 24.8 and
411 26.0 vol %), with small to medium apparent average size (240-480 μm , average 340 μm), rich in
412 silicates, that would have deep absorption bands around 1 μm and 2 μm (Table 1). The overall
413 darkness can be explained by the high abundance of matrix that hides silicate absorption bands.
414 The lack of phyllosilicate signature agrees with the classification as type 3.00 that denotes the
415 absence of significant hydration of the meteorites of the petrographic A. EM 200 has no
416 phyllosilicates signatures on XRD, but very low amounts of phyllosilicates on IR transmission of
417 its matrix. Its proportions of phyllosilicates is thus very low and does not show on the reflectance
418 spectra, making it similar to the 3.00 chondrites.

419 The second spectral group is composed of NWA 5958, Aydar 003, EM 100, NWA 11086. These
420 meteorites are all in the petrographic group B. They show a rather sharp maximum around 0.6 μm ,
421 together with a shallow absorption band around 1 μm (Fig. 6b). While there is variability in spectral
422 VIS-NIR slopes, these four meteorites show spectral signatures of phyllosilicates at 0.7, 0.9 and
423 1.1 μm (absorptions by $\text{Fe}^{2+}\text{Fe}^{3+}$). The case of EM 100 is particular since signatures of
424 phyllosilicates can be also found at 1.9 μm (absorptions by H_2O) and 2.3 μm (absorptions by X-
425 OH). Those spectra show small absorptions bands, which can be explained by a high proportion of
426 matrix (44.1-75.5 vol%, average 55.8 vol%). The phyllosilicate spectral signatures in this spectral
427 subgroup are in agreement with the significant aqueous alteration of the matrix of this petrographic
428 subgroup. The equivalent albedo (at 550 nm) of EM 100 and NWA 11086 are relatively high

429 compared to C2 chondrites and meteorites from spectral group 1 (Fig. 7), which may be related to
430 a lower abundance of opaque phases (7 vol% for EM 100 and 2 vol% for NWA 11086).

431 The third spectral group has higher VIS-NIR spectral slope values than the first two groups, and
432 deeper absorption band around 0.9-1 μm , as well as slight to no absorption bands around 2 μm
433 (Fig. 6c). They also show low albedo at 550 nm, slightly higher than the first spectral group, ranging
434 0.07-0.12, with Sierra Gorda 009 as an exception (0.19) (Fig. 7). The meteorites in this spectral
435 group are most of the meteorites of the petrographic group C: Dho 2066, LoV 200, Sierra Gorda
436 009, NWA 12474, and the rare chondrite Kakangari (Fig. 3); with the addition of Acfer 094 from
437 petrographic group A (Fig. 1) and NWA 8781 from petrographic group B (Fig. 2).

438 Compared to the two first spectral groups, showing very small absorptions features, this spectral
439 subgroup has higher VIS-NIR slopes and deeper absorption bands around 0.9 μm and small to no
440 absorption bands around 2 μm , which agrees lower abundances of matrix (0-66.8 vol%, average
441 41.8 vol%) and higher chondrule abundances (22.7-74.5 vol%, average 41.5 vol%) and size (130-
442 1050 μm , average 485 μm) (Table 1). Indeed, with a general higher proportion of silicates and less
443 fine-grained matrix, spectral features around 0.9 μm and 2 μm appear deeper on the spectra. In
444 greater detail, Kakangari, Dhofar 2066 and NWA 12474 have spectra reflecting a high matrix
445 abundance, hiding the silicates absorption bands. Kakangari has also a matrix composition rich in
446 enstatite, a magnesium-rich pyroxene with less absorption bands around 2 μm than iron-rich
447 pyroxene. LoV 200 show a positive VIS-NIR slope with shallow and broad features near 950 nm.
448 Its spectrum reflects the absence of matrix with abundant (66 vol%) chondrules, composed of a
449 high proportion of pyroxene in form of enstatite. In addition, the abundant opaques (24.4 vol%),
450 mostly under the form of metal, have no IR absorption signature but can explain the overall red
451 VIS-NIR slope. Acfer 094 and Sierra Gorda 009 have similar flat to slightly negative VIS-NIR
452 slopes with a small absorption band around 0.9 μm . Sierra Gorda 009 has a spectrum reflecting the

453 absence of matrix with abundant chondrules creating the absorption around 900 nm. The lack of
454 broad absorption band around 2 μm is explained by the pyroxene composition low in iron
455 ($\text{Fe}_{1.42\pm 0.39}\text{W}_{0.88\pm 0.63}$) that have shallower absorption bands than iron-rich pyroxene. We can see a
456 small absorption band around 1.9 μm due to potential iron oxides left from terrestrial weathering
457 even after the leaching process. Acfer 094 is part of the petrographic group A but spectral group 3,
458 due to its more positive slope and deeper absorption band around 0.9 μm than the three other
459 meteorites of petrographic group A. Indeed, Acfer 094 is spectrally different than petrographic
460 group A, explained by its different silicate composition, richer in iron, in addition to less abundant
461 matrix and more abundant chondrules, creating deeper absorption bands. NWA 8781 is from
462 petrographic group B, but has spectral characteristics from spectral group 3. It has a slightly deeper
463 absorption band and more positive VIS-NIR slope than other meteorites of the petrographic group
464 B. This can be explained by a lower matrix abundance, with higher proportion of silicates than
465 other meteorites of petrographic group B.

466 The spectral group number 4 is defined by the spectra showing narrow absorption bands around
467 1050 nm with sharp walls of the absorption band and usually slightly positive general VIS-NIR
468 slopes (Fig. 6d). They have medium equivalent albedo at 550 nm, from 0.1 to 0.18 (Fig. 7). The
469 meteorites in this spectral group are the Rumuruti chondrites, Awsserd and NWA 12472 from
470 petrographic group D. Awsserd and NWA 12472 display very similar spectra showing a 1050 nm
471 absorption band and a broad and shallow absorption band around 2000 nm, with positive VIS-NIR
472 slopes. The fourth spectral group spectra are explained by the iron-rich olivine dominated
473 chondrules ($\text{Fa}_{37.2}$ and $\text{Fa}_{40.9}$) (Table 1). Indeed, Rumuruti chondrites have the most iron-rich
474 olivines in all chondrites, creating deep absorption bands around 1 μm .

475 The fifth spectral group shows spectra with strong and relatively narrow absorption band around 1
476 μm with a faint absorption around 1900 nm (Fig. 6e). The visible maximum has a rounded shape

477 around 750 nm and the general VIS-NIR slope or the spectra can vary from slightly negative to
478 slightly positive but all of them show similar absorption bands. NWA 12334, LoV 051 and
479 Coolidge have low abundance of matrix (0, 17.2, 19.3 vol%) (Table 1), creating a spectrum
480 dominated by silicates with deep absorption bands around 1 and 2 μm . The smaller chondrules of
481 Coolidge explains the less pronounced bands of its spectrum compared to LoV 051. NWA 12334
482 is from petrographic group F (Fig. 5) but has spectral similarities from spectral group 5 (Fig. 6e).
483 It has indeed shallower absorption bands than the other meteorites from petrographic group F (Fig.
484 6f). The equivalent albedo is high for NWA 12334 (0.16), LoV 051 (0.15) and Coolidge (0.14)
485 (Fig. 7).

486 The sixth spectral group (Fig. 6e) comprises the meteorites from petrographic group F (Fig. 5), the
487 primitive achondrites NWA 12480 (Acapulcoite) and NWA 6592 (Lodranite), and the ordinary
488 chondrites JaH 846 from petrographic group E (Fig. 4f). This spectral group shows spectra with
489 similar absorption bands positions as the previous spectral group, with deeper absorption and more
490 positive VIS-NIR slopes (Fig. 6f). Indeed, those meteorites have recrystallized matrix due to
491 metamorphism. Those recrystallized silicates explain the deep absorptions bands in this group.
492 Members of this spectral group have variable equivalent albedo at 550 nm, with medium albedo
493 for JaH 846 (0.12) and higher albedo for NWA 12480 (0.4) (Fig. 7). JaH 846's spectrum has a deep
494 and narrow absorption band around 950 nm, with a broad absorption band around 1950 nm
495 reflecting its unusual high proportion of pyroxene, with some chondrules dominated by pyroxene
496 (Table 1). NWA 12480 shows the deepest absorption band around 950 nm, with a deep band around
497 1950 nm due to pyroxene-dominated composition as well.

498 **4.2 The impact of sample preparation**

499 The surface of most asteroids is covered with regolith (e.g. (132173) Ryugu, Jaumann et al., 2019),
500 explaining why laboratory meteorite spectra are often done on powdered samples. However,
501 asteroids can also present larger blocks on their surface, or even surfaces almost devoid of regolith
502 such as asteroid (101955) Bennu (Lauretta et al., 2019). Therefore, we chose to measure IR
503 reflectance spectra of raw and polished section samples in addition to powdered samples. This
504 allows assessing whether sample preparation changes the asteroid-meteorite spectral connections,
505 an aspect that is rarely discussed in literature.

506 Some meteorites, achondrites or ordinary chondrites, have powdered samples with higher
507 reflectance spectra than the raw and polished section samples (Fig. 8A), but other samples,
508 especially carbonaceous chondrites, show higher reflectance on raw sample spectra compared to
509 powdered samples (Fig. 8B). In addition, independently from the chondrites group, the powdered
510 samples show a redder spectrum than the raw and polished sections (Fig. 8, Fig. 9). Indeed,
511 powdered samples have higher slopes at 1 μm as well as 2 μm than polished sections and raw
512 samples for all spectral groups (Fig. 9). We know that grain size, more generally texture, impact
513 the VIS-NIR slope and the depth of absorption bands of a spectrum (Ross et al., 1969; Johnson and
514 Fanale, 1973, Cloutis et al., 2018). The redder VIS-NIR slope of powdered samples compared to
515 raw samples was observed by Beck et al. (2021) on the CM chondrite Aguas Zarcas. This redder
516 VIS-NIR slope of powdered sample spectra can be explained by red sloped phases becoming more
517 visible when finely mixed with other minerals (Ross et al., 1969) (Fig. 9). It could also be due to
518 the grinding changing the mixture and the grain sizes. Indeed, when grinding the sample, the
519 powder becomes an intimate amalgam, linear in a single-scattering albedo space. Raw samples on
520 the contrary are a real mixture of individual phases and the mixture should be linear in reflectance

521 space. Thus, the grinding can make the matrix of the meteorites more visible than on raw samples,
522 darkening and reddening the spectra. The organic matter and the alteration phases in their matrix
523 being more visible on powdered samples, it will darken and redden the spectra and hide the silicates
524 absorption bands. This explains why most carbonaceous chondrites (spectral group 1-3), with high
525 matrix abundances, have darker and redder spectra for powdered samples than raw samples (Fig.
526 7). Additionally, polished sections are one of the most used preparations of meteorites as it is the
527 easiest way to assess the petrographic context. Also, polished sections are easily available from
528 meteorite repositories, whereas raw samples for rare and small meteorites may be more difficult to
529 obtain in loan. Thus, being able to measure infrared reflectance spectra of a polished section is
530 undoubtedly interesting. For polished sections, sample preparation influences the reflectance
531 spectra for carbonaceous chondrites, especially spectral group 1 to 3, but less for other chondrites.
532 Indeed, for carbonaceous samples, it creates redder VIS-NIR slopes than raw samples (Fig. 8B,
533 Fig. 9). Due to the influence of polished section preparation on the reflectance spectra
534 measurement, if raw or powdered sample present a different comparison than the spectra on
535 polished sections for the same meteorite, we give more weight to the raw and powdered samples
536 spectra.

537 **4.3 Comparison of ungrouped and grouped meteorites**

538 The samples chosen in this study are ungrouped chondrites or meteorites from rare groups. In
539 addition to their petrographic and chemical specificities, we now compare their spectral properties
540 with that of well-studied meteorite groups to determine if their particularities stand out in infrared
541 spectroscopy.

542 For the first spectral group, NWA 12957, NWA 11750 and Chwichiya 002 have broadly similar
543 petrography but differ by oxygen isotopic composition and opaque abundances (as reflected also

544 by their different magnetic properties) (Fig. 1, Table 1). Thus, their spectra are similar, except for
545 a small difference in position of the maximum peak around 600 nm. The absence of clear absorption
546 bands makes their spectra similar to typical spectra of CM, CO, CV or CR chondrites, but their
547 spectra do not resemble any of those chondrites' spectra (Fig. 10a). For the second spectral group,
548 the closest meteorite spectra are of CM chondrites (Fig. 10b). We can see that indeed Aydar 003
549 and NWA 5958 spectra are similar to a CM spectrum, only with bluer VIS-NIR slopes. NWA 5958
550 is known to have CM-related petrography and bulk chemistry (Jacquet et al., 2016), so the IR
551 spectra are similar. A difference between NWA 5958 and CM chondrites is the absence of small
552 absorption band at 750 nm and the bluer VIS-NIR slope in the former. NWA 11086, classified as
553 CM-an, has a spectrum resembling CM chondrites, with a slightly more positive VIS-NIR slope.
554 Finally, EM 100 has a spectrum resembling CM chondrites, but with a very strong VIS-NIR slope
555 and appears overall much brighter than typical CM chondrites.

556 In the third spectral group, LoV 200 has a spectrum resembling enstatite chondrites (EC) spectra,
557 similar to another CH chondrite studied (Cloutis et al., 2012) (Fig. 10c). Indeed, LoV 200 has a
558 high proportion of pyroxene in the form of enstatite, which is a common feature with enstatite
559 chondrites. NWA 12474 has an IR spectrum similar to CR2 chondrites, with a bluer VIS-NIR slope
560 (Fig. 10c). Kakangari has a spectrum with features in between those of ordinary chondrites and
561 enstatite chondrites (Fig. 10c). This is explained by the high matrix abundance resembling
562 carbonaceous chondrites hiding the absorption bands, and with a matrix rich in enstatite,
563 resembling EC (Table 1). It has a metal abundance closer to ordinary chondrites, in addition to
564 olivine and pyroxene compositions in between EC and H ordinary chondrites (Weisberg et al.,
565 1996) (Table 1). Acfer 094 has a spectrum resembling the Kakangari spectrum, with a faint
566 absorption around 0.9 μm , and resembles spectra of CR chondrites (Fig. 10c). Dho 2066 has a
567 petrography resembling CM chondrites, but shows shallower absorption around 1 μm and a more

568 positive VIS-NIR slope, resembling CH meteorites or CY meteorites (King et al., 2019) (Fig. 10c).
569 NWA 8781 resembles most CR meteorite spectra, with shallower absorption bands that could be
570 explained by the lower abundance of silicates compared to CR chondrites, or a low thermal
571 metamorphic grade (Eschrig et al., 2020) (Fig. 10c). Sierra Gorda 009 has a spectrum similar to L
572 chondrites (Fig. 10c). It has indeed no matrix and abundant chondrules, explaining the spectrum
573 resembling ordinary chondrites (Table 1).
574 For the fifth spectral group, LoV 051 spectrum resembles ordinary L meteorites (Fig. 10d). It has
575 low matrix abundance, with high proportion and larger chondrules than CR chondrites (Table 1).
576 NWA 12334 is a LL-an and its spectrum resembles LL chondrites spectra well (Fig. 10d).
577 Finally, for the sixth spectral group, JaH 846 and NWA 12480 have deep absorption bands around
578 1 μm and 2 μm , dominated by silicates, and are thus closer to ordinary chondrite spectra (here
579 compared to L or LL spectra) (Fig. 10e).

580 5 Potential parent bodies

581 5.1 Qualitative comparison of reflectance spectra of meteorite powders to asteroid 582 observations

583 In this section we present a qualitative comparison of infrared spectra of the studied ungrouped or
584 rare meteorites to asteroids, in order to find resemblances, and hence potential parent bodies. For
585 this comparison we used DeMeo et al. (2009) taxonomy based on more than 400 infrared spectra
586 of asteroids in the 0.45 to 2.45 μm range.

587 As surfaces of large asteroids are usually covered by regolith, and usually parent body research is
588 done on powdered samples, we compare, in a first step, asteroid reflectance spectra with reflectance
589 spectra of our meteorite powders. We first match the spectra qualitatively (qualitative match, called
590 QM in the following), and then compare quantitative spectral parameters (§5.2). The preferred

591 asteroid matches to the meteorite spectra are presented for all samples in Table 2. In addition, to
592 complete the comparison of meteorites to the asteroids, we use the equivalent geometric albedo
593 and test if different spectral groups of meteorites match the albedo of the associated asteroid groups
594 (Fig. 7). This low angle reflectance is then comparable to the albedo of the asteroids.

595 For the first spectral group, we observe that the powdered meteorite reflectance spectra have a QM
596 to C-complex asteroids (Table 2, Fig 6a). C-type reflectance spectra have low to medium VIS-NIR
597 slope with small to no features (DeMeo et al., 2009), consistent with carbonaceous chondrites. In
598 details, Ch- and Cgh-type asteroids are classically linked to CM chondrites (Vilas and Gaffey,
599 1989; Vilas et al., 1993; Rivkin, 2012; Rivkin et al., 2015; Lantz et al., 2013; Burbine, 2014;
600 McAdam et al., 2015; Vernazza et al., 2016; Vernazza et al., 2017), but they have also been
601 matched with multiple other meteorites groups, such as ureilite (Jenniskens et al., 2009), CI
602 (Johnson and Fanale, 1973; Cloutis et al., 2011), CR (Hiroi et al., 1996; Sato et al., 1997), K
603 (Gaffey, 1980). In contrast, Cg- and B-type asteroids have not been matched to any meteorite group
604 yet (Vernazza et al., 2015). This first spectral group matches best to C- and Cg-types. NWA 12957
605 is closer to Cg-type with a maximum around 650 nm and a pronounced UV drop-off (DeMeo et
606 al., 2009). Chwichiya 002, EM 200 and NWA 11750 match C-type asteroid spectra. In addition,
607 the spectra of the first spectral group of meteorites show low equivalent albedo, similar to low
608 albedo asteroids C-, B- and D-types (Fig. 7), consistent with the match to C-complex (Fig. 6).

609 The second spectral group also has a QM with C-complex asteroids (Fig. 6b). Aydar 003 shows a
610 good resemblance with Ch-type asteroids, with the same slight positive VIS-NIR slope and the
611 small absorption band around 750 nm. NWA 5958 powder spectrum has no clear match, in between
612 B-type and Ch-type asteroids. NWA 11086 has a slight absorption bands around 1 μm and no
613 features around 2 μm , resembling C-complex spectra, but its positive VIS-NIR slope does not
614 resemble the C-complex. We were therefore unable to propose a good match for this sample.

615 Similarly, EM 100 cannot be matched to any asteroid. Indeed, its spectrum resembles Ch-type
616 asteroids but with a much higher spectral VIS-NIR slope, especially visible on powdered samples.
617 The second spectral group has a general low equivalent albedo (Fig. 7), similar to asteroids of the
618 C-, B- and D-complexes. NWA 11086 and EM 100 are exceptions and show higher albedo (Fig.
619 7), potentially due to very positive VIS-NIR slopes.

620 The third spectral group is composed of meteorites with a QM with the X-complex asteroids (Fig.
621 6c). X-complex asteroids have spectra with medium to high VIS-NIR slope. Xc-type asteroids
622 present featureless spectra, and are linked to enstatite chondrites and aubrites (Zellner 1975, Zellner
623 et al., 1977, Vernazza et al., 2009b, 2011, Shepard et al., 2015; Vernazza et al., 2016). Xk- and Xe-
624 type asteroids show features around 0.9-1 μm , associated to low-FeO pyroxene (Clark et al., 2004;
625 Gaffey et al., 1989; DeMeo et al., 2009). Xk-type asteroids are supposed parent bodies of
626 mesosiderites, but Xe-type have no associated meteorite groups yet (Vernazza et al., 2009). LoV
627 200 matches Xe- or Xk-types asteroids, only with a flatter VIS-NIR slope for the raw sample. Dho
628 2066 spectrum is very similar to LoV 200 and resemble Xe-, Xk- or Xc-types. Acfer 094, NWA
629 8781, Sierra Gorda 009 and Kakangari resemble the Xe- and Xk-types spectra but with slight
630 differences in band positions and depths. K meteorites were associated to C-complex by Gaffey
631 (1980), but here we rather associate the Kakangari sample to X-type complex as the 1 μm band
632 position resembles more X-complex asteroids. X-complex asteroids are not represented in Fig. 7.
633 Their albedo is divided into three classes with distinct albedo: E (> 0.30) M ($0.0075 < M < 0.30$) and
634 P (< 0.075) (DeMeo and Carry, 2013). The third spectral group of meteorites has an equivalent
635 geometric albedo ranging between 0.07-0.2, associated to M-type. The spectral matching to X-type
636 asteroids is consistent with the albedo comparison, more specifically to the M-subcategory.

637 The meteorites of the fourth spectral group have a QM with the K-type asteroids (Fig. 6d). This
638 type is the potential parent body of CV, CO, CR and CK meteorites (Cruikshank and Hartmann,

639 1984; Sunshine et al., 2007; Clark et al., 2009; Cloutis et al., 2012; Vernazza et al., 2016). In this
640 study, the meteorites linked to the K-type asteroids are R chondrites. Sunshine et al. (2007) linked
641 Rumuruti meteorites to the A-type asteroids using band positions, chemical composition of olivine
642 and melting models. In this study, we found that the A-type reflectance spectrum shows too deep
643 absorption bands and too high VIS-NIR slope compared to these two samples. The two meteorites
644 have absorption bands around 1050 nm that is attributed to olivine. The equivalent geometric
645 albedo of those Rumuruti are in the same range of the K-type asteroids (and also L-type asteroids),
646 which corroborate their match. This could be due to a difference in grain size. A-type asteroids
647 could have larger grain sizes, thus deeper absorption and brighter albedo, compared to K-type and
648 powdered samples or Rumuruti with smaller grain sizes.

649 The fifth spectral group of meteorites has a QM with the S-complex (Fig. 6e). S-complex asteroids
650 are the most common asteroids in the inner region of the asteroids belt (between 2 and 2,5 AU of
651 semi-major axis) (Gradie and Tedesco 1982; DeMeo and Carry 2013). This complex is usually
652 associated to ordinary chondrites (Vernazza et al., 2016). It has also been associated to
653 mesosiderites, acapulcoite/lodranite and winonaite (Gaffey et al., 1993), or to angrite (Rivkin et
654 al., 2007). Differentiating between the asteroid types inside the S-complex (such as S, Sv, Sr, Sq,
655 Sw) is difficult without using multiples parameters in a PCA (DeMeo et al., 2016). In this study,
656 some spectral groups were not differentiated. We only made a difference between the S-, Sr-, and
657 Sv-types on one side, and the Sa- and Sq-types on the other side. Those two latter show broader
658 absorption bands around 1 μm , and Sa-type asteroids show a shallower absorption around 2 μm .
659 LoV 051 is a good match to S- and Sr-type asteroids with less positive VIS-NIR slopes. Its
660 equivalent geometric albedo resembles lower albedo S-type asteroids (Fig. 7). Coolidge has a
661 similar spectrum as LoV 051 with less absorption bands, thus not match to any clear asteroids, but
662 is closer to S-type asteroids. NWA 12334 also matches the S- and Sr-types spectra on powdered

663 sample. It shows a spectrum similar to ordinary chondrite spectra, but the type 6 of the chondrite
664 creates slightly deeper bands.

665 Finally, the sixth spectral group of meteorites is a QM to S-types with deeper absorption bands,
666 such as Sa-, Sq- and Sv-types (Fig. 7f). Sv-type asteroids have spectra intermediate to S- and V-
667 types. They have the narrowest features of the S-complex, resembling V-type spectra. They are
668 pyroxene-rich spectra showing deep absorption bands around 1 and 2 μm . This feature is a good
669 match with the spectra of NWA 12480. JaH 846 matches the Sq- and Sv-types, with deeper
670 absorption bands. The sixth meteorite spectral group's equivalent geometric albedos are variable.
671 NWA 12480 has spectra similar to Sv- and V-types asteroids. Its equivalent geometric albedo is
672 high and is closer to V-type asteroids (Fig. 7). NWA 12334 has an equivalent geometric albedo
673 close to lower albedo S-type asteroids corresponding to its spectra shape associated to S- and Sq-
674 types asteroids (Fig. 7). Finally, the spectra of JaH 846 are similar to S-type asteroids. Its equivalent
675 geometric albedo is slightly lower than the albedo of the S-complex (Fig. 7). Indeed, the albedo of
676 S-type asteroids are higher than the albedo of type 3 ordinary chondrites, usually linked to S-
677 complex. This cannot be explained by space weathering, as it darkens the surface of the asteroids
678 and changes the VIS-NIR slope of the spectra (Pieters and Noble, 2016). An explanation is that the
679 S-complex asteroids are not covered by type 3 ordinary chondrite material, but more thermally
680 processed material of type 4 or above (Beck et al., 2020). This agrees with the hypothesis of a fast
681 accretion followed by fragmentation and brecciation of the surface of S-type asteroids (Vernazza
682 et al., 2014).

683 **5.2 Quantitative comparison of IR parameters of meteorite powders and asteroid** 684 **spectra**

685 To improve the comparison between spectra from meteorites and asteroids, we compared
686 quantitative spectra parameters. We used the following parameters: 1 μm and 2 μm bands positions
687 (nm), the 1 and 2 μm bands depths (%), the VIS-NIR slope of the spectra in the range of 1 μm and
688 2 μm (nm^{-1}). Each spectral parameter was plotted against each other parameter to investigate every
689 combination (e.g. Fig. 12).

690 We consider that a meteorite sample is matching an asteroid spectrum when the spectral parameters
691 of the asteroid are in the range of the meteorite parameters (Fig. 11, Fig. 12). For the band positions,
692 the range is limited by the resolution of asteroid spectra used in our work. The DeMeo et al. (2009)
693 endmember spectra are acquired with a step of 50 nm in wavelength, while the resolution of the
694 spectra of the meteorites is better, with a step of 20 nm. For the band depths and the slope
695 parameters, the ranges are defined by standard deviations. The standard deviation is calculated for
696 each parameter, using all 25 meteorites of the same sample preparation. Thus, the standard
697 deviations of one parameter represent the possible variation of compositions in-between
698 meteorites, without being influenced by the sample preparation (Fig. 12, Fig. 13). As a result, if
699 the difference between the parameters of an asteroid and of a meteorite is smaller than the standard
700 deviation of all meteorites, we considered that the asteroid and the meteorite have similar
701 parameters, i.e. compositions. The range of possible matches for each meteorite describes an
702 ellipsoid (semi-axis a, b) in each plot (Fig. 11, Fig. 12). A match between an asteroid (x, y) and a
703 meteorite (h, k) is thus described by the equation : $\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} \leq 1$. The result of the
704 parameters matching is reported in Table 2 and (Fig. S1).

705 We computed which asteroids have the highest recurrence match (HRM) to the studied meteorites
706 (Table 2). We defined a matching score calculated as the number of plots where a certain asteroid
707 spectrum matches a specific meteorite, normalized to the total of plots where the meteorite is
708 compared, the latter depending on the number of features of the spectrum (Table 2). Indeed, not all
709 spectra show features at 1 or/and 2 μm . When the band depths were $< 2.5\%$, we considered that as
710 no absorption bands, thus no feature. The first, second and third spectral group show no 2 μm band
711 and some of them no 1 μm features (Fig. 6a, 6b and 6c). Spectra showing no absorption bands
712 around 1 as well as around 2 μm can only be compared through slope parameters, lowering the
713 matching score. The three first spectral groups of meteorites also display very shallow 1 μm band
714 depths $< 4.5\%$, with no clear silicate absorption bands. Thus, we chose to compare those meteorite
715 spectra only to asteroid spectra showing no clear silicates absorption bands: C- and X-complexes.
716 The spectral group 4 to 6 show clear silicates absorption bands (Fig. 6d, 6e and 6f). They display
717 1 μm band depths (6-69 %) and 2 μm band depths (4-34 %), except for spectral group 4 and Sierra
718 Gorda 009 (spectral group 5) with 2 μm band depths $< 4\%$. Those spectral groups are compared to
719 asteroid spectra showing similar silicates absorption bands: Q-, O-, R-, K-, V-types and S-complex.
720 For the first spectral group, meteorite powdered samples have HRM to C-complex asteroids (Table
721 2). All three have HRM with Cgh- and Ch-types. NWA 11750 and NWA 12957 also have HRM
722 with B-type asteroids from the C-complex. Chwichiya 002 and EM 200 have HRM with Xc- and
723 Xe-types from the X-complex. The difficulty in distinguishing C- and X-complexes is explained
724 in §2.3.3.

725 The second spectral group has an HRM with C-complex as well. Aydar 003 have an HRM with
726 Cg-, Cgh and Ch-types. NWA 11086 have an HRM to C-, Cg-, and Xk-types. NWA 5958 has
727 HRM with Ch-, Cgh- and B-types. Finally, EM 100 have an HRM with C-type (Table 2). For the
728 third spectral group meteorite powders have a more variable HRM. The QM was with the X-

729 complex (§4.1), but the HRM is with X-complex as well as with C-complex (Table 2). LoV 200,
730 Sierra Gorda 009 and Dho 2066 have an HRM with X-complex and C-complex asteroids. NWA
731 8781, Acfer 094 and Kakangari powdered samples have an HRM with C-complex. NWA 12474
732 has an HRM with B-type asteroids. For the fourth spectral group, the powdered samples QM was
733 best with K-type asteroids. Both meteorites have an HRM to K-type, but also S-complex asteroids
734 (Table 2). Indeed, in band position and depth, the S-complex asteroids are similar to K-type
735 asteroids. The shape of the bands is not a parameter considered in the quantitative parameter
736 comparison, but the meteorites of this spectral group have sharp V-shaped absorption bands,
737 characteristic of K-type asteroids, showing that the QM is necessary for some spectra. In the fifth
738 spectral group, powdered samples match S-complex asteroids, more precisely S- and Sr-types
739 asteroids, as observed with the QM (Table 2). Although, NWA 12334 has an HRM with Sq-type,
740 as well as Q- and K-types. The sixth spectral group also has HRM with S-complex asteroids, as
741 observed with QM (Table 2). JaH 846 has an HRM with Sr-type. NWA 12480 has an HRM with
742 V-type and R-type asteroids. The QM was with Sv-type asteroids (Fig. 6) the intermediate spectra
743 between V- and S-types asteroids.

744 Finally, we calculated the Closest Matching Asteroids (CMA), which represent the closest asteroid
745 to a meteorite sample in all parameter plots. This is calculated by minimizing the norm of the vector
746 defined by a meteorite (M) to an asteroid (A) : $\|\overrightarrow{MA}\| = \sqrt{(P_{xM} - P_{xA})^2 + (P_{yM} - P_{yA})^2}$, with
747 P_x the spectra parameter chosen on the x-axis and P_y the spectral parameter on the y-axis (Table
748 2).

749 The CMA for the first spectral group are B-, Cg- and Ch-types asteroids (Table 2). This is in line
750 with the QM and HRM that linked those meteorites to the C-complex. The second spectral group's
751 CMA are B-, C-, Cg- and Ch-types, also in line with the C-complex linked to those meteorites

752 (Table 2). The third spectral group of meteorites have a CMA of C-complex as well as X-complex,
753 just as seen with the HRM (Table 2). LoV 200, Dho 2066 and NWA 8781 have a CMA of X-type
754 (Xc-, Xe- and Xk-types). Acfer 094, Kakangari, Sierra Gorda 009 and NWA 12474 have a CMA
755 of C-complex asteroids. The fourth meteorite spectral group all have QM to K-type asteroids (Fig.
756 6), but the CMA are K- and Sq-types asteroids (Table 2). For the fifth spectral group of meteorites,
757 the CMA are S-complex asteroids, especially S- and Sv-types (Table 2). Finally, for the sixth
758 spectral group, the CMA are R-, V- or S-types (Table 2). NWA 12334's CMA are Sq-type
759 asteroids. NWA 12480's CMA are V- and R-types asteroids, similar to the HRM. Finally, JaH
760 846's HRM are Sr-types asteroids, and its CMA are R-type asteroids, which are one end-member
761 or the Sr-type asteroids, an intermediate between S- and R-types.

762 **5.3 Effect of texture on matching**

763 In addition to the comparison of meteorite powdered samples, we also compared raw and polished
764 section meteorite spectra to asteroid spectra. While we discussed how sample preparation affects
765 the reflectance spectra in §4.2, we now discuss how it impacts the connection to potential parent
766 bodies.

767 **5.3.1 Raw meteorites samples**

768 As a general behavior, raw meteorite samples were observed to have bluer spectra than meteorite
769 powders (explained §4.2). Consequently, several of our asteroid matches are impacted by sample
770 preparation. In particular, many associations to spectral types were found to be B-type for raw
771 meteorites, while being C-type or even S- and X-types for meteorite powders (Table 2). In the case
772 of meteorite powders with association to S-complex, the spectral match generally remained within
773 the S-complex in the case of raw samples (Table 2). The two studied R chondrites were
774 qualitatively associated to K-types asteroids for powder spectra, and raw spectra as well. For the
775 quantitative comparison of meteorites to asteroids, some changes were found between raw samples

776 and powders, with spectra from raw samples tending to be associated to S-complex or Q-type
777 asteroids.

778 **5.3.2 Polished sections**

779 Polished sections are widely used in Earth Sciences. However, this non-natural sample preparation
780 may induce artifacts if one wants to compare with remote observations of small bodies. For the
781 QM, polished samples were matched similarly to powder and raw samples (Table 2). One exception
782 is NWA 11750, which was matched to Cg-type for powdered sample, while matched to Xc-type
783 when prepared as a polished section. In the case of the quantitative comparison, polished section
784 spectra usually match the same asteroid types as either raw or powdered sample preparation.
785 Exceptions can be found, such as Kakangari and Dho 2066, where all three types of sample
786 preparations show different matches for the quantitative comparison. We conclude that the spectral
787 study of polished section can be useful, but should best be used in complement to other sample
788 preparations, or when other types of samples are unavailable.

789 **5.4 Potential parent bodies**

790 **5.4.1 Bus DeMeo taxonomy matching**

791 After the QM, HRM and CMA of meteorites to asteroids was done in this study, we also submitted
792 our meteorites to the online Bus DeMeo taxonomy matching tool ([http://smass.mit.edu/cgi-](http://smass.mit.edu/cgi-bin/busdemeoclass-cgi)
793 [bin/busdemeoclass-cgi](http://smass.mit.edu/cgi-bin/busdemeoclass-cgi)), to see if it provided similar results. The Bus DeMeo taxonomy matching
794 is based on powdered samples, but we also tried matching data from raw samples and polished
795 sections. Even if most of the results are comparable to our results, Bus DeMeo taxonomy matching
796 showed limitations. Firstly, almost all spectra from the raw samples are falsely matched to B-type
797 asteroids, due to their bluer slopes (see §4.2). Most of the raw sample spectra matched to B-type
798 asteroids show silicates absorption bands, in contrary to B-type asteroids spectra, invalidating those
799 matches. Also, some of the meteorites showing silicate absorption bands are wrongly matched to

800 C- or X-complexes showing slight to no silicate absorption bands, and for some samples no match
801 could be found.

802 **5.4.2 Potential parent bodies of this study**

803 In our study, the first spectral group is composed of three ungrouped type 3.00 carbonaceous
804 chondrites and one C3 carbonaceous chondrite that have a high proportion of matrix (Table 1).

805 With the sample preparation influencing the spectra, we matched them to either Cg-type or B-type
806 asteroids (Table 2). Interestingly, both of those asteroid types have not been linked to any group of
807 meteorites yet (Vernazza and Beck, 2017). This match could demonstrate that those three
808 meteorites create a new spectral group of meteorites with the association of a potential parent body.

809 In the second spectral group, Aydar 003 and NWA 5958 can be matched with Ch-type asteroids
810 (Table 2), in line with CM meteorites that have been linked to Ch- and Cgh-types asteroids
811 (Vernazza and Beck, 2017). EM 100 and NWA 11086 also have some similarities with CM-like
812 spectra, but cannot be matched to Ch-type asteroids. Indeed, they show higher albedo and spectral
813 VIS-NIR slopes (Fig. 7). Thus, they may originate from an unidentified yet slightly hydrated
814 carbonaceous asteroid type.

815 The third spectral group of meteorites are linked to the X-complex (Fig. 6c). Indeed, LoV 200, Dho
816 2066 and NWA 8781 are linked to Xe-type or Xk-type asteroids. Xe-type asteroid have not been
817 linked to any meteorite groups yet (Vernazza et al., 2016) and NWA 8781, Dho 2066 and LoV 200
818 could be potential samples of this asteroid type. Kakangari and Sierra Gorda 009 are both linked
819 to X-complex as well as C-complex asteroids. They could therefore be matched to both C- and X-
820 complexes (Table 2). For Acfer 094 and NWA 12474, we are not able to link those meteorites to
821 any types of asteroid. Using the three sample preparations, we can see that their matching is not
822 straightforward (Table 2) and would require further investigations, although they would probably
823 originate from asteroids resembling X-complex. NWA 12474 is indeed matched to B-type due to

824 its bluer slope but shows slight silicate absorption bands, invisible on B-type asteroids. In this
825 subgroup, chondrites of various petrology match the same asteroid types, such as Kakangari, Sierra
826 Gorda009, Dhofar 2066 and NWA 8781. Those chondrites probably do not originate from a
827 common parent body, as their petrography are too different. Nonetheless, they do probably come
828 from parent bodies displaying similar VIS-NIR spectra as the X-complex. This demonstrate a limit
829 of the spectral matching, as some mineralogy, although different, result in similar spectra thus a
830 similar match.

831 The fourth spectral group (Rumuruti chondrites) is matched to K-type asteroids (Fig. 6d). Rumuruti
832 meteorites were previously linked to the A-type asteroids (Sunshine et al., 2007), but K-type shows
833 a better match in our analysis, as the A-type reflectance spectrum shows too deep absorption bands
834 and too high VIS-NIR slope compared to our meteorite's spectra.

835 The fifth spectral group is composed of LoV 051, Coolidge and SaH 00177. They are linked to S-
836 , Sr- or Sv-type asteroids (Table 2). This suggests that the S-complex of asteroids is not only
837 composed of ordinary chondrites or primitive achondrites, but may also host metamorphosed
838 carbonaceous chondrites. SaH 00177, studied only as polished sections, also match S-, Sr, and Sv-
839 types asteroids. The sixth spectral group is composed of two metamorphosed ordinary chondrites
840 and two primitive achondrites. We link the three samples to asteroid spectra with deep absorption
841 bands, such as Sv-, Sq- and Sa-types asteroids. The acapulcoite matches Sv-type asteroids, NWA
842 12334 (LL6-an) matches S- or Sq-type asteroids, and JaH 846 is linked to Sr- or Sv-type asteroids.
843 Finally, NWA 6592 and Mulga (west), only studied as polished sections, are good matches to Sa-
844 or Sq-types asteroids.

845 6 Conclusion

846 We studied 25 meteorites, mostly ungrouped chondrites or meteorites from rare groups. We first
847 separated them into six meaningful petrographic groups. The same meteorites were studied by VIS-
848 NIR reflection spectroscopy, to compare their spectra to asteroid reflectance spectra. The spectra
849 obtained of all meteorites were grouped into 6 spectral groups. Those spectral groups mirror the
850 petrographic groups, with only a few exceptions (Acfer 094, NWA 8781, EM 200, NWA 12334,
851 and JaH 846). VIS-NIR spectra are therefore a good proxy for the overall petrography, and as such
852 a meaningful tool to match meteorites and potential parent asteroids. In order to better match real
853 asteroid surfaces that can be dusty and/or rocky, we measured raw samples in additions to
854 powdered samples. The two types of samples have different spectral characteristics. Raw samples
855 show bluer VIS-NIR slopes than powders, especially for carbonaceous chondrites. We also
856 compare the powders' spectra to polished sections spectra, as polished sections are widely available
857 for study. We show that polished section spectra can be good equivalent to raw sample spectra,
858 with similar spectral parameters and matching to asteroids. The matching of meteorite samples to
859 asteroids were made by qualitative as well as quantitative matching of different parameters (bands
860 depths, bands positions and slopes at 1 and 2 μm). Interestingly, some ungrouped meteorites are
861 matched to asteroid types which were not linked to any grouped meteorites before this study.
862 Indeed, the three ungrouped carbonaceous C3.00 chondrites (spectral group 1), representing very
863 pristine carbonaceous chondrite material, are matched to Cg-type or B-type asteroids. In addition,
864 three slightly metamorphosed and aqueously altered ungrouped carbonaceous chondrites from the
865 spectral group 3 are good matches to Xe-type asteroids, which were also not matched to any other
866 grouped meteorites before. Some meteorites from the spectral group 2, showing CM-like
867 petrography, resemble Ch-type asteroids, but showing more hydration bands than the asteroid

868 spectra. This shows that those samples must originate from an unidentified yet slightly hydrated
869 carbonaceous asteroid type. Those samples should be further investigated, as the current mission
870 OSIRIS-REx showed that the asteroid (101955) Bennu should be a CM-like asteroid with more
871 hydration than usual CM chondrite spectra (Lauretta et al., 2019). In addition, some
872 metamorphosed carbonaceous chondrites, from our spectral group 5 and 6, matched with the S-
873 complex asteroids, usually presented as parent bodies of ordinary chondrites and primitive
874 achondrites, suggesting that the S-complex of asteroids may also host metamorphosed
875 carbonaceous chondrites. We also compared our matching results to the Bus DeMeo taxonomy
876 online program. Their matches were similar to ours for the powdered samples, unlike for the raw
877 samples where the Bus DeMeo program wrongly matched the samples mainly to B-type asteroids.
878 This emphasizes our conclusion that the use of only powdered samples in parent body research
879 may be misleading, as asteroid's surfaces not only display regolith, but also large blocks (e.g.,
880 asteroid (101955) Bennu). In conclusion, the study of ungrouped chondrites and other rare
881 meteorites reveal new links to yet unmatched asteroids, exemplifying the importance of the study
882 of this material which represent a large fraction of the diversity of the meteoritic material available
883 for study, and could sample many unmatched asteroids. As such, these meteorites give insight into
884 the composition and mineralogy of unstudied asteroids.

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1203

1204 **Figures Legends :**

1205 Figure 1 : BSE images of chondrites from petrographic group A. a: Chwichya002 (C3.00-ung); b :
1206 NWA 11750 (C3.00-ung); c : NWA 12957 (C3.00-ung); d: Acfer 094 (C2-ung). Scale bar is
1207 identical for all images. All images have been made with similar contrast and luminosity
1208 parameters.

1209 Figure 2: BSE images of chondrites from petrographic group B: a : Aydar 003 (CM1/2); b : EM
1210 100 (C2-ung); c : NWA 11086 (CM-an); d : EM 200 (C3); e : NWA 5958 (C2-ung); f: NWA 8781
1211 (C-ung). Scale bar is identical for all images. All images have been made with similar contrast and
1212 luminosity parameters.

1213 Figure 3: BSE images of chondrites from petrographic group C: a: LoV 200 (CH3); b : Dho2066
1214 (C-ung); c: Kakangari (K3); d: NWA 12474 (CR3); e: SG 009 (chondrite-ung). Scale bar is
1215 identical for all images. All images have been made with similar contrast and luminosity
1216 parameters.

1217 Figure 4: BSE images of chondrites from petrographic group C: a : Awsserd (R4) ; b: NWA 12472
1218 (R3). BSE images of chondrites from petrographic group E: c: LoV 051 (C3-ung) ; d : Coolidge
1219 (C4-ung) ; e : Sah00177 (C3/4-ung) ; f: JaH 846 (OC3). Scale bar is identical for all images. All
1220 images have been made with similar contrast and luminosity parameters.

1221 Figure 5: BSE images of meteorites from petrographic group F: a : Mulga West (C5/6-ung) ; b:
1222 NWA 12334 (LL6-an) ; c: NWA 12480 (Acapulcoite) ; d: NWA 6592 (Lodranite). Scale bar is
1223 identical for all images. All images have been made with similar contrast and luminosity
1224 parameters.

1225 Figure 6 : Meteorite spectra (solid line) compared to asteroid spectra (dashed lines). Spectra were
1226 normalized at 0.55 and then offset for clarity. Number 1-6 are spectral group of meteorites. “L” is
1227 for leached powdered samples; ACA: acapulcoite; Chond-ung : chondrite ungrouped.

1228 Figure 7 : Equivalent geometric albedo of meteorites and asteroid complexes. Number 1-6 are
1229 spectral groups of meteorites. Equivalent albedo from reflectance at 550nm, phase angle $g=30^\circ$,
1230 calculated with factor from Figure 3 of Beck et al., (2021). Geometry albedo of asteroids families
1231 from DeMeo and Carry (2013). ACA: Acapulcoite; Chond-ung : ungrouped chondrite.

1232 Figure 8 : Reflectance for different sample preparations. A: Sierra Gorda 009 samples, from
1233 petrographic group C and spectral group 3; B: Chwichiya 002 sample, from petrographic group A
1234 and spectral group 1. P.S. : polished section.

1235 Figure 9 : Slopes (nm^{-1}) at 1 (cold colors) and 2 μm (warm colors) for different sample preparation
1236 for all spectral groups.

1237 Figure 10: Visible-near-infrared reflectance spectra of studied samples (solid line) compared to
1238 spectra of selected groups of meteorites (dashed lines). Spectra were normalized at 0.55 μm and
1239 then offset for clarity. Number 1-6 are spectral group of meteorites. No comparison for the spectral
1240 group 4 was made, as meteorites in this spectral group belong to the well-established R chondrite
1241 group. “L” is for leached powdered samples; ACA : acapulcoite; Chond-ung : chondrite ungrouped.

1242 Figure 11: Plots of spectral parameters for NWA 11750 (C3.00-ung), belonging to petrographic
1243 group A and spectral group 1. Asteroid Highest Recurrent Match (HRM) is Cg-type. Yellow

1244 ellipses correspond to bulk sample spectrum data; Green ellipses correspond to powder sample
1245 spectrum data; Red ellipses correspond to polished section spectrum data. Chond-ung : chondrite
1246 ungrouped; P.S.: polished section.

1247 Figure 1: Plots of spectral parameters of LoV 051 (C3-ung), belonging to petrographic group E and
1248 spectral group 5. Asteroid Highest Recurrent Match (HRM) is Sr-type. Yellow ellipses correspond
1249 to bulk sample spectrum data; Blue ellipses correspond to leached powder sample spectrum data;
1250 Red ellipses correspond to polished section spectrum data. Chond-ung : chondrite ungrouped;
1251 achondrite-prim : primitive achondrites; P.S.: polished section; Powder-L : powdered leached
1252 sample.

1253 Table 1 : Petrographic characteristic of meteorites.

1254 Table 2 : Asteroids matching to meteorites.

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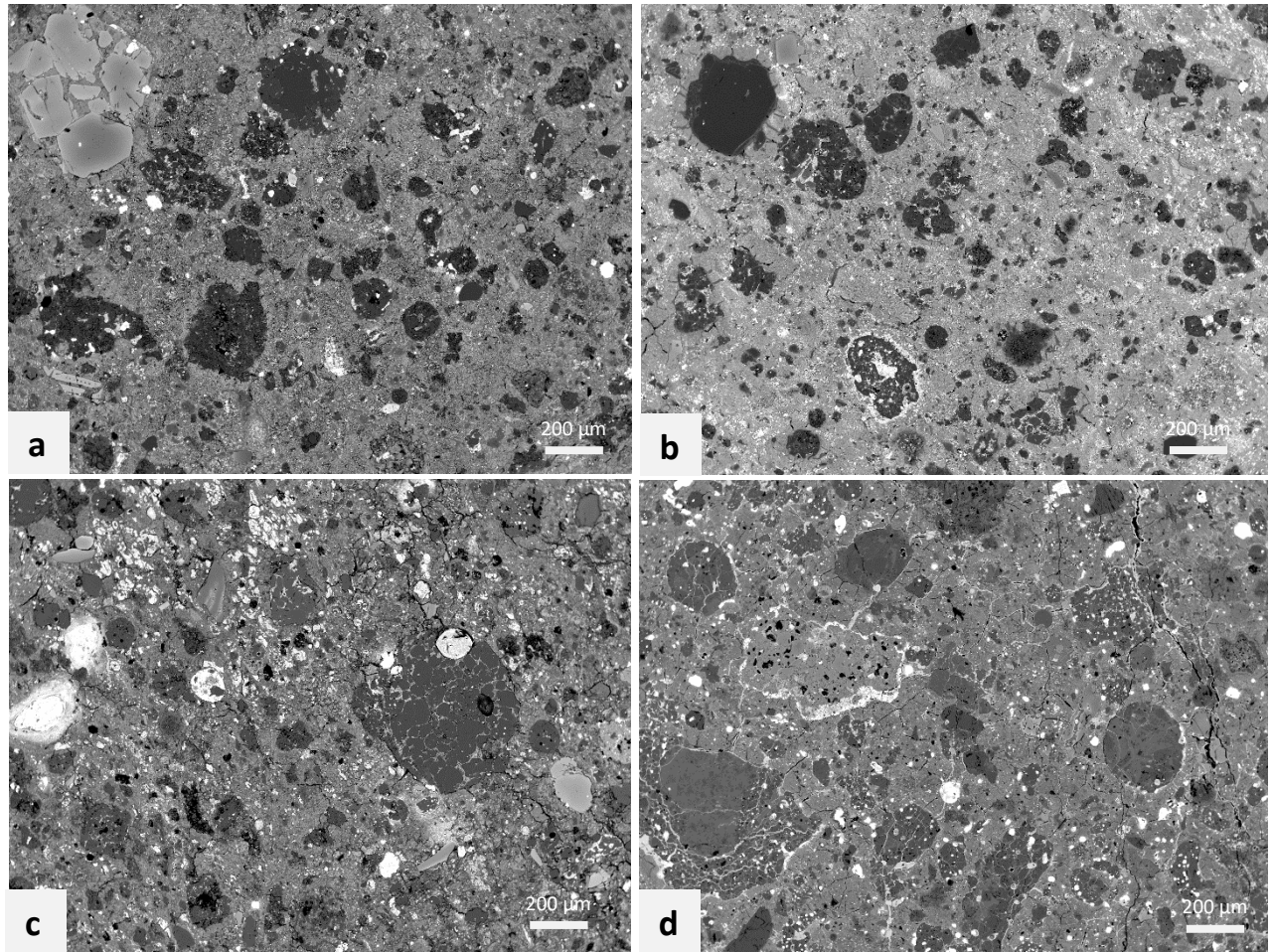


Figure 2 : BSE images of chondrites from petrographic group A. a : Chwichya002 (C3.00-ung); b : NWA 11750 (C3.00-ung); c : NWA 12957 (C3.00-ung); d : Acfer 094 (C2-ung). Scale bar is identical for all images. All images have been made with similar contrast and luminosity parameters.

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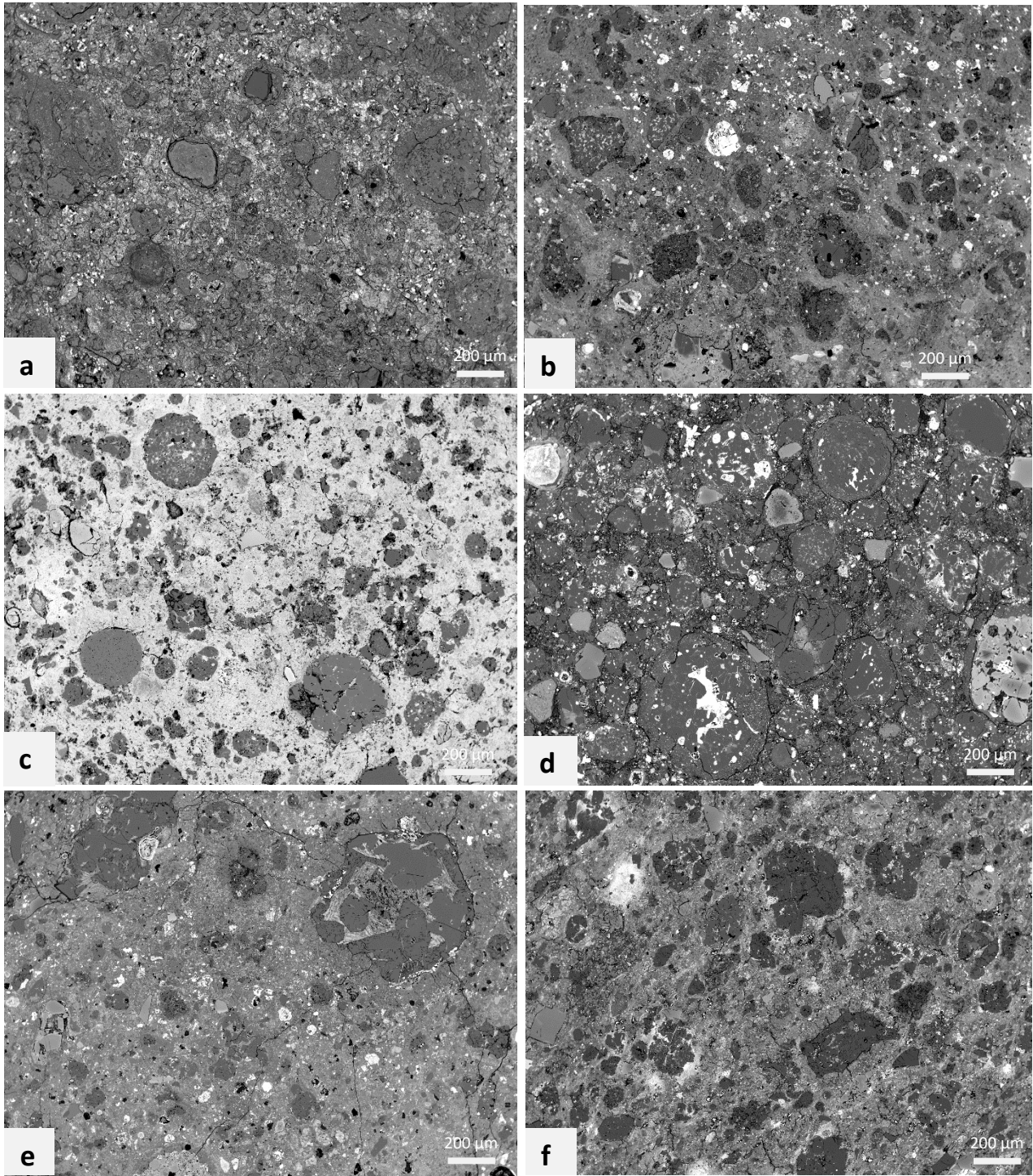


Figure 3: BSE images of chondrites from petrographic group B: a : Aydar 003 (CM1/2); b : EM 100 (C2-ung); c : NWA 11086 (CM-an); d : EM 200 (C3); e : NWA 5958 (C2-ung); f: NWA 8781 (C-ung). Scale bar is identical for all images. All images have been made with similar contrast and luminosity parameters.

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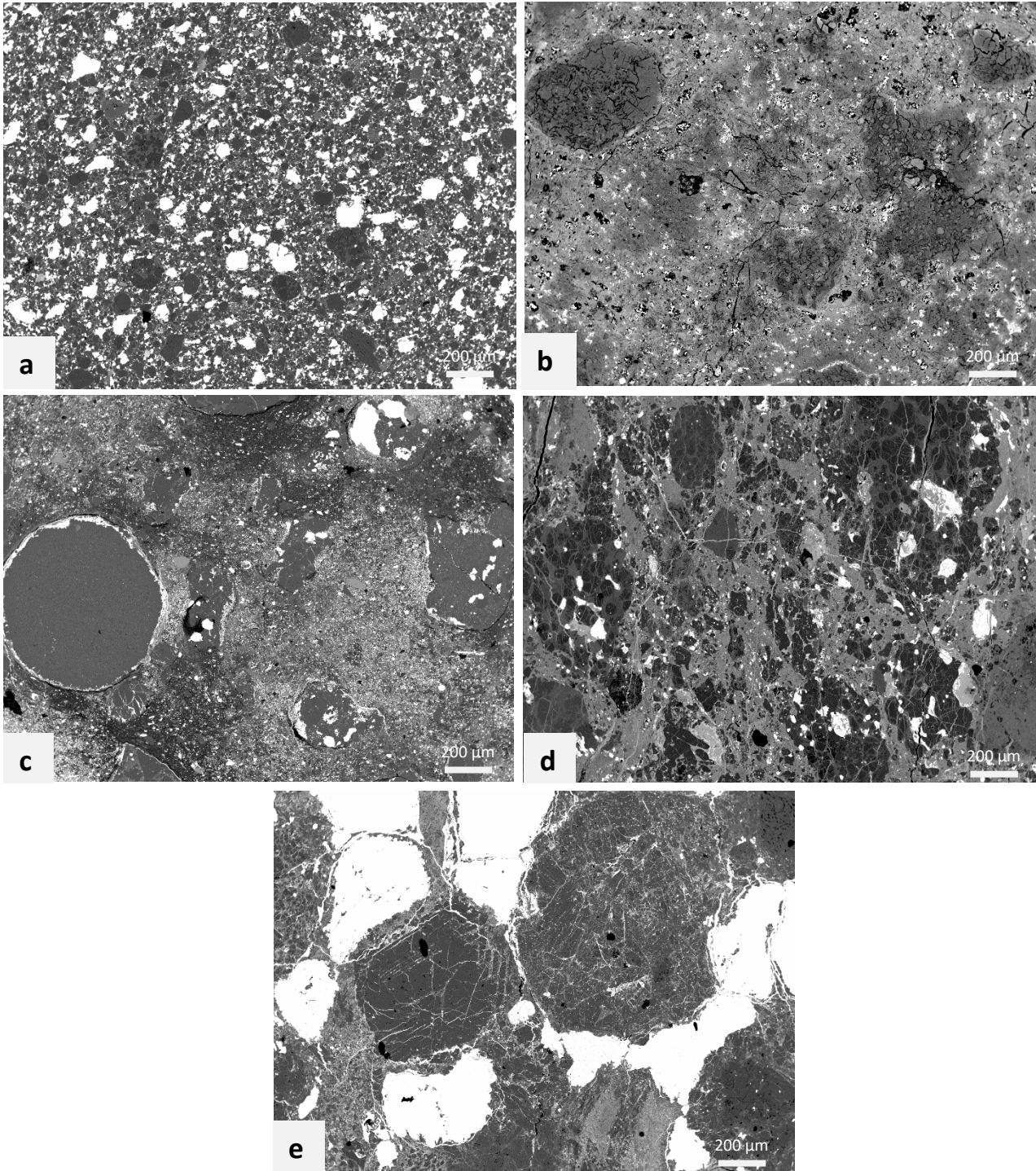


Figure 4: BSE images of chondrites from petrographic group C: a: LoV 200 (CH3); b : Dho2066 (C-ung); c: Kakangari (K3); d: NWA 12474 (CR3); e: SG 009 (chondrite-ung). Scale bar is identical for all images. All images have been made with similar contrast and luminosity parameters.

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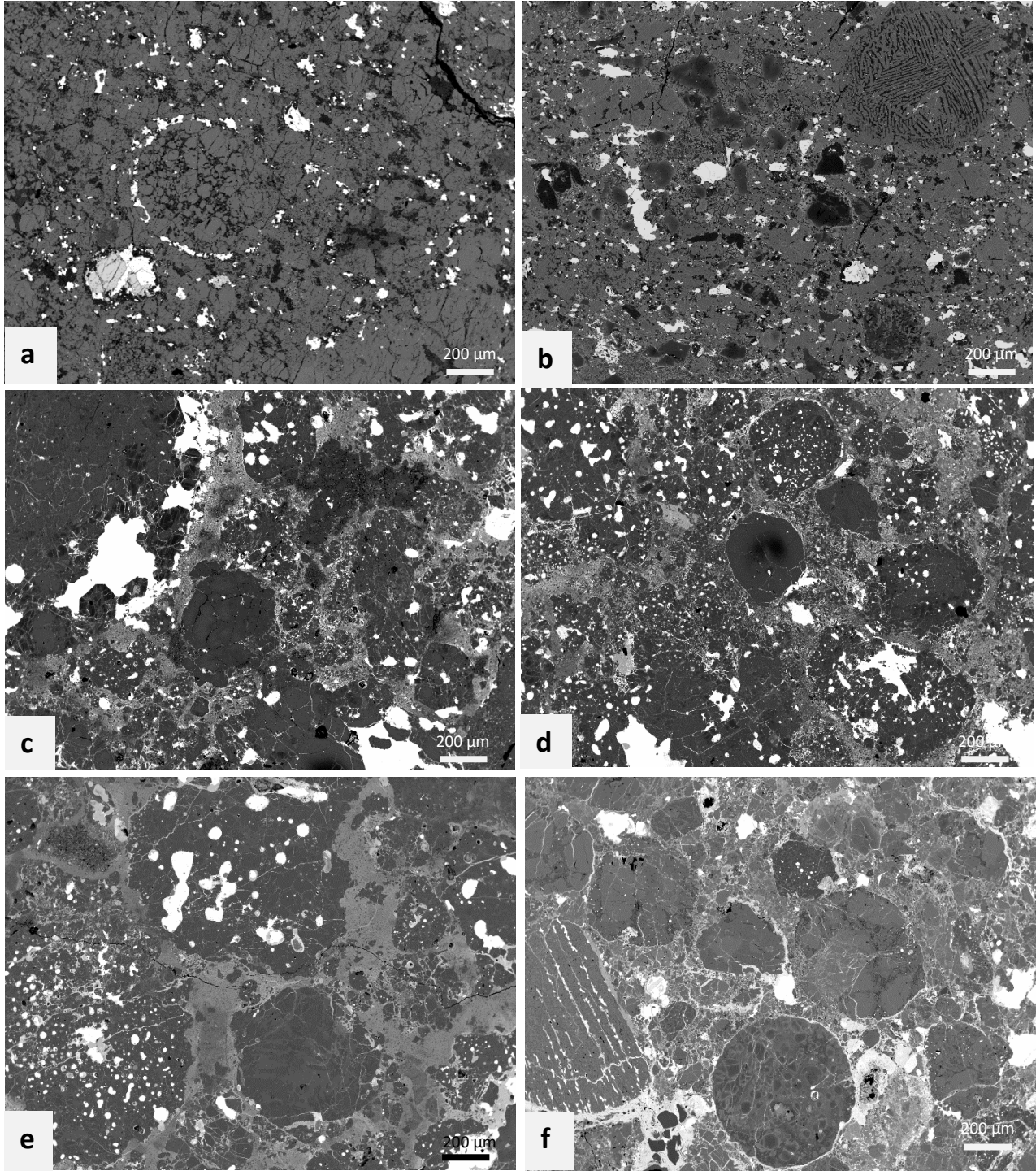


Figure 5: BSE images of chondrites from petrographic group C: a : Awsserd (R4) ; b: NWA 12472 (R3). BSE images of chondrites from petrographic group E: c: LoV 051 (C3-ung) ; d : Coolidge (C4-ung) ; e : Sah00177 (C3/4-ung) ; f: JaH 846 (OC3). Scale bar is identical for all images. All images have been made with similar contrast and luminosity parameters.

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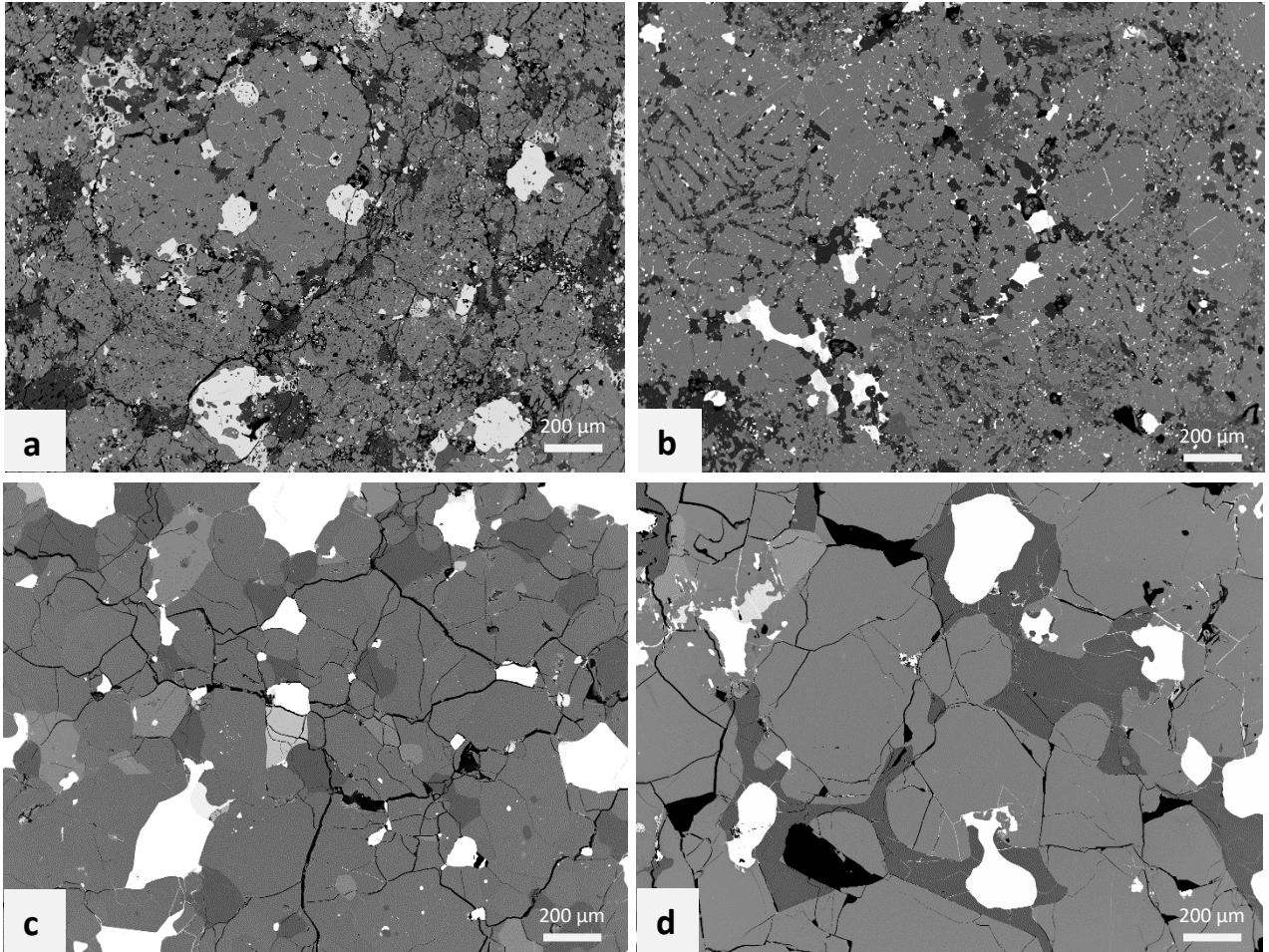
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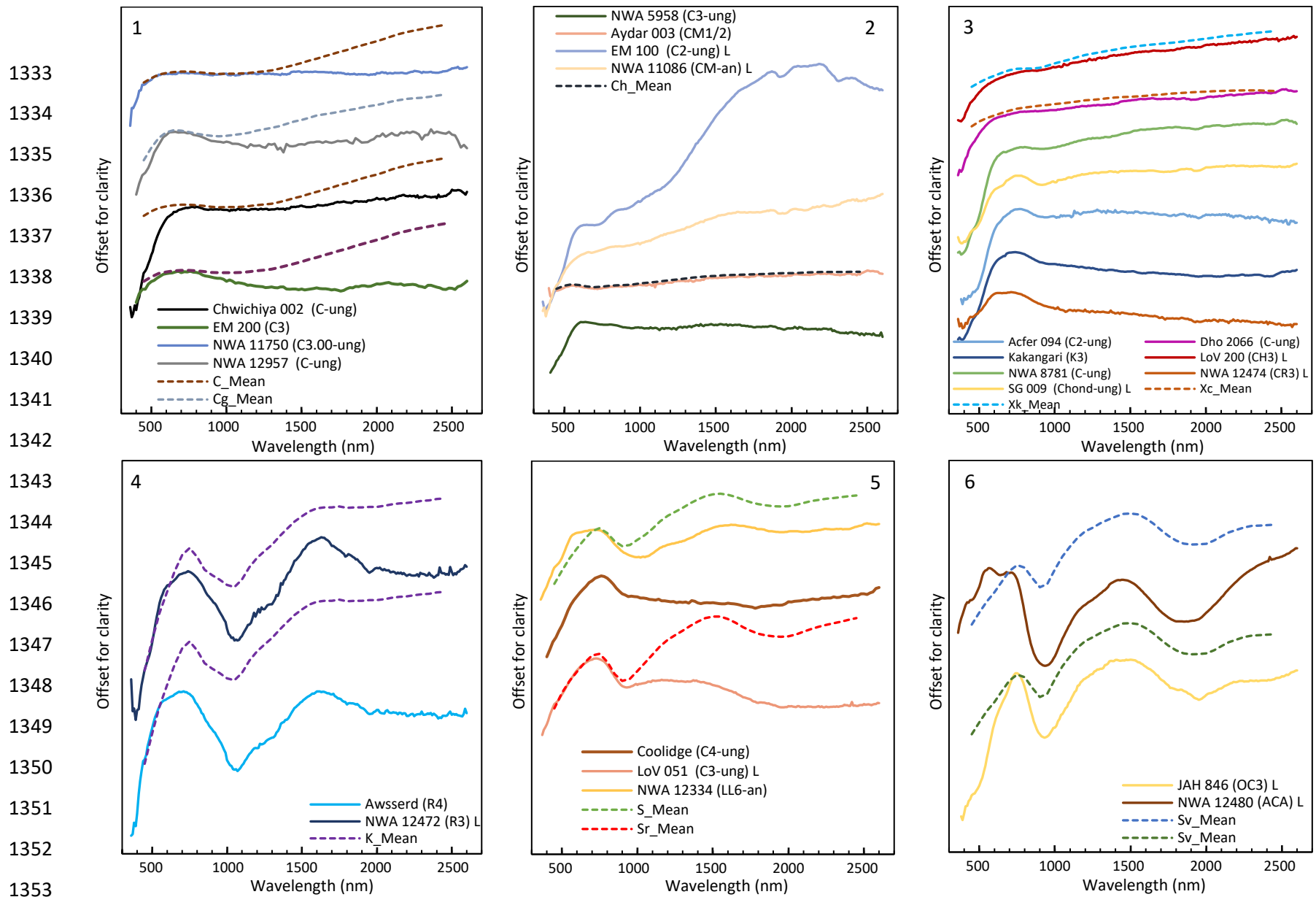
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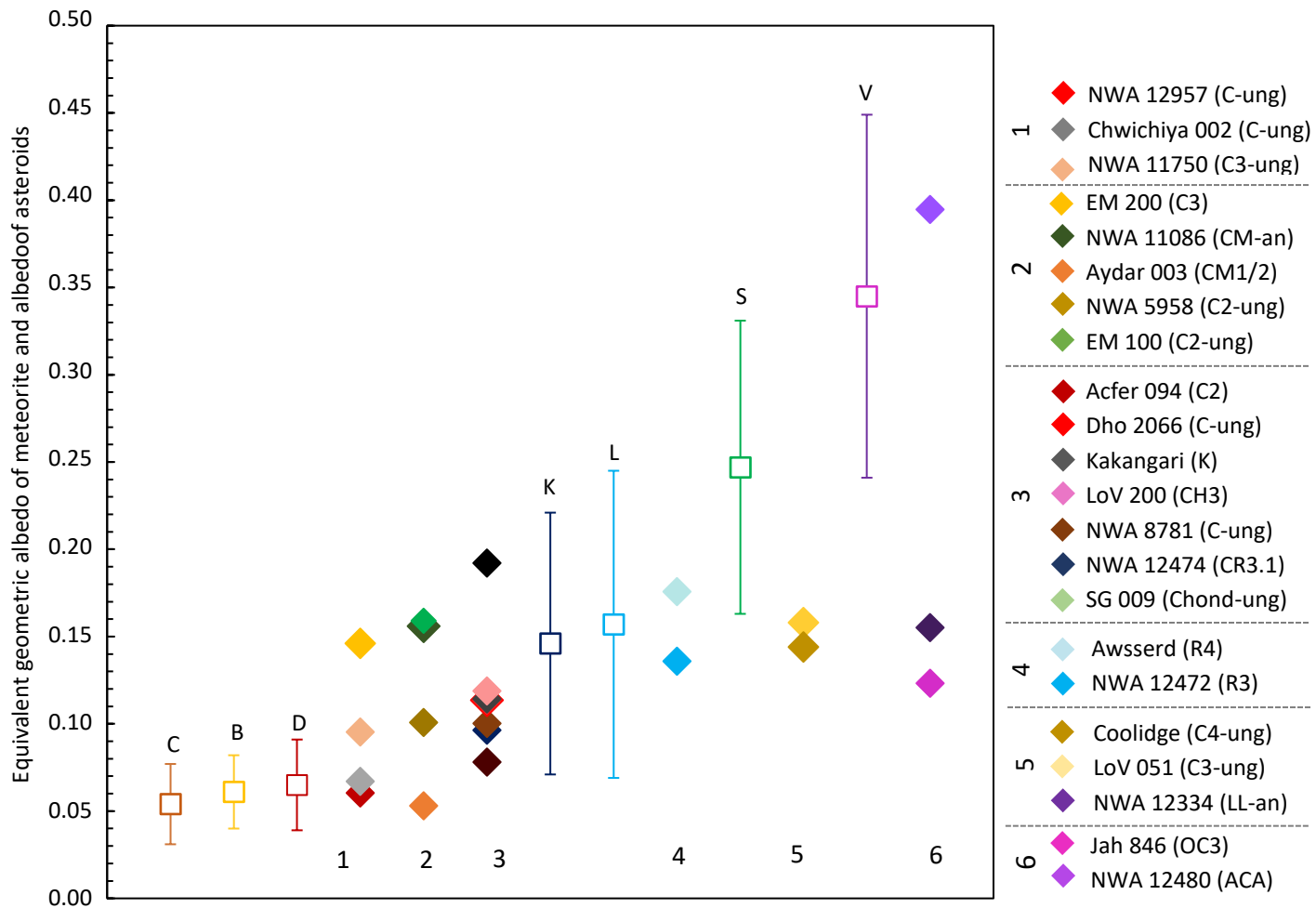
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Figure 6: BSE images of meteorites from petrographic group F: a : Mulga West (C5/6-ung) ; b: NWA 12334 (LL6-an) ; c: NWA 12480 (Acapulcoite) ; d: NWA 6592 (Lodranite). Scale bar is identical for all images. All images have been made with similar contrast and luminosity parameters.



1354 Figure 7 : Meteorite spectra (solid line) compared to asteroid spectra (dashed lines). Spectra were normalized at 0.55 μm and then offset for clarity. Number 1-6 are spectral group
 1355 of meteorites. "L" is for leached powdered samples; ACA: acapulcoite; Chond-ung : chondrite ungrouped.

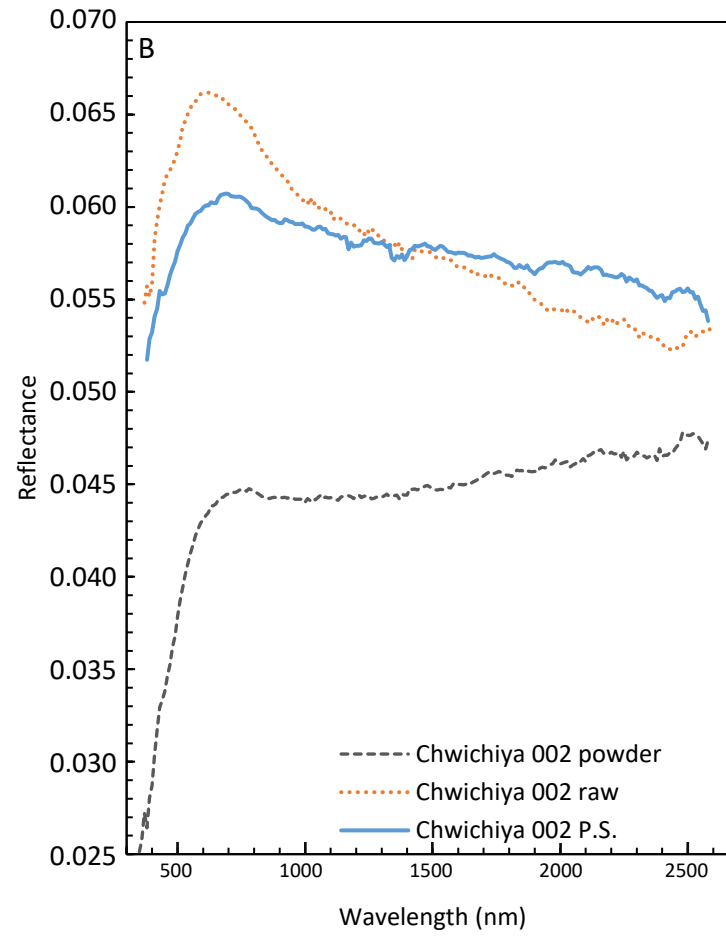
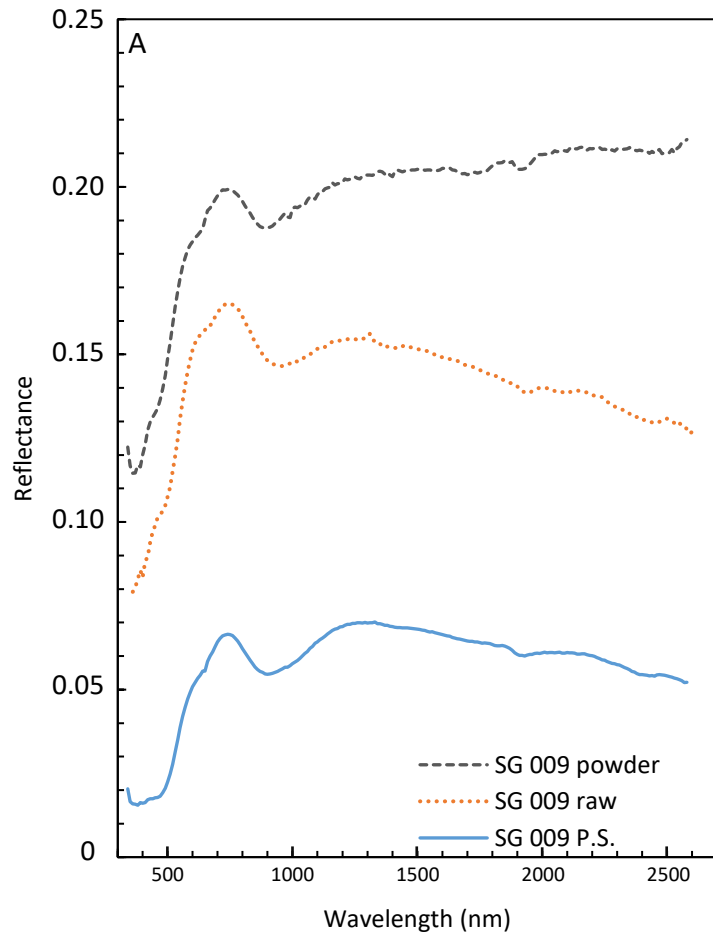


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1357 *Figure 8 : Equivalent geometric albedo of meteorites and asteroid complexes. Number 1-6 are spectral groups of meteorites. Equivalent albedo from reflectance at 550nm, phase*
 1358 *angle $g=30^\circ$, calculated with factor from Figure 3 of Beck et al., (2021). Geometry albedo of asteroids families from DeMeo and Carry (2013). ACA: Acapulcoite; Chond-ung :*
 1359 *ungrouped chondrite.*

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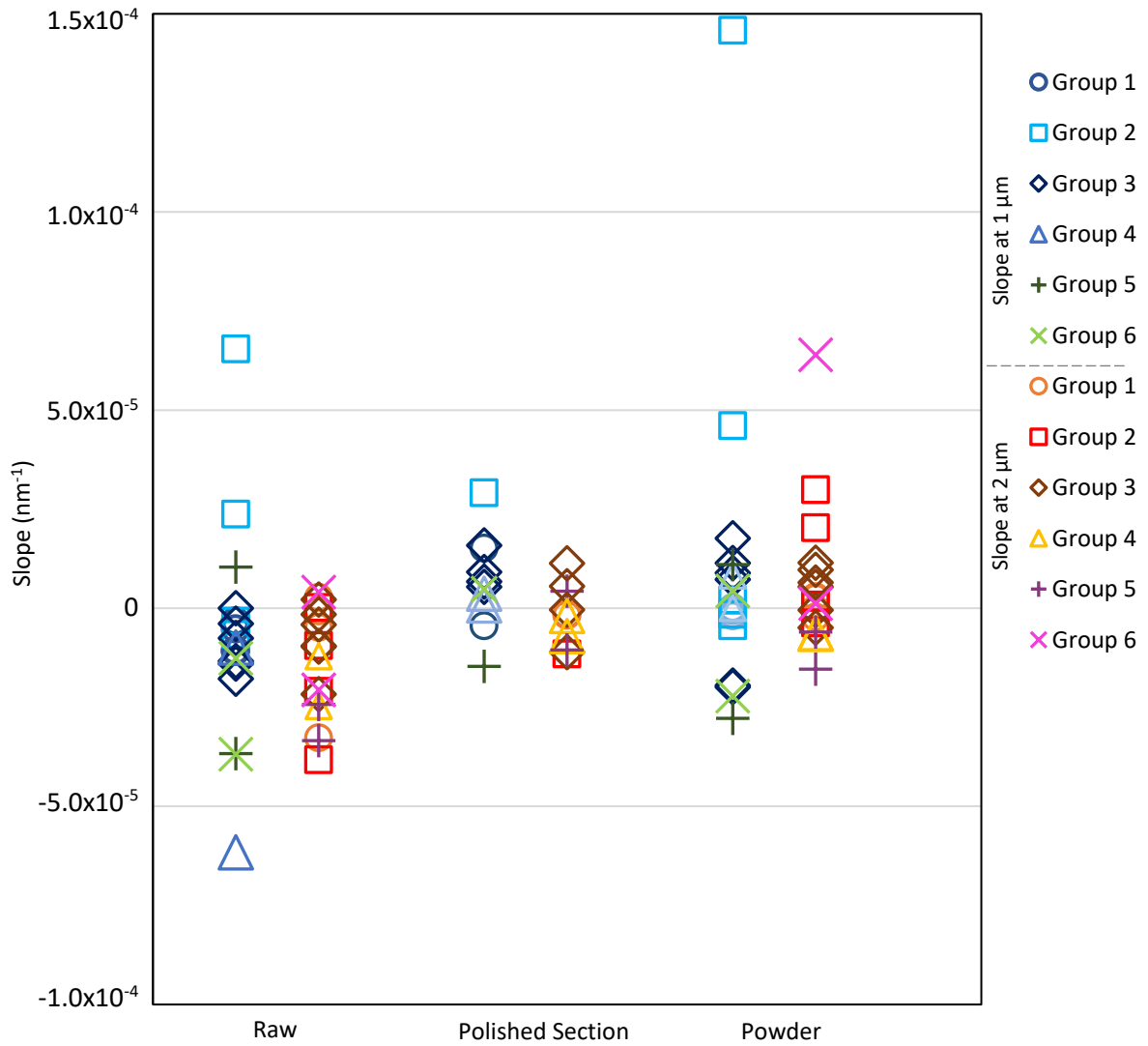
1363 *Figure 9 : Reflectance for different sample preparations. A: Sierra Gorda 009 samples, from petrographic group C and spectral group 3; B: Chwichiya 002 sample, from*
 1364 *petrographic group A and spectral group 1. P.S. : polished section.*

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Figure 10 : Slopes (nm⁻¹) at 1 (cold colors) and 2 μm (warm colors) for different sample preparation for all spectral groups.

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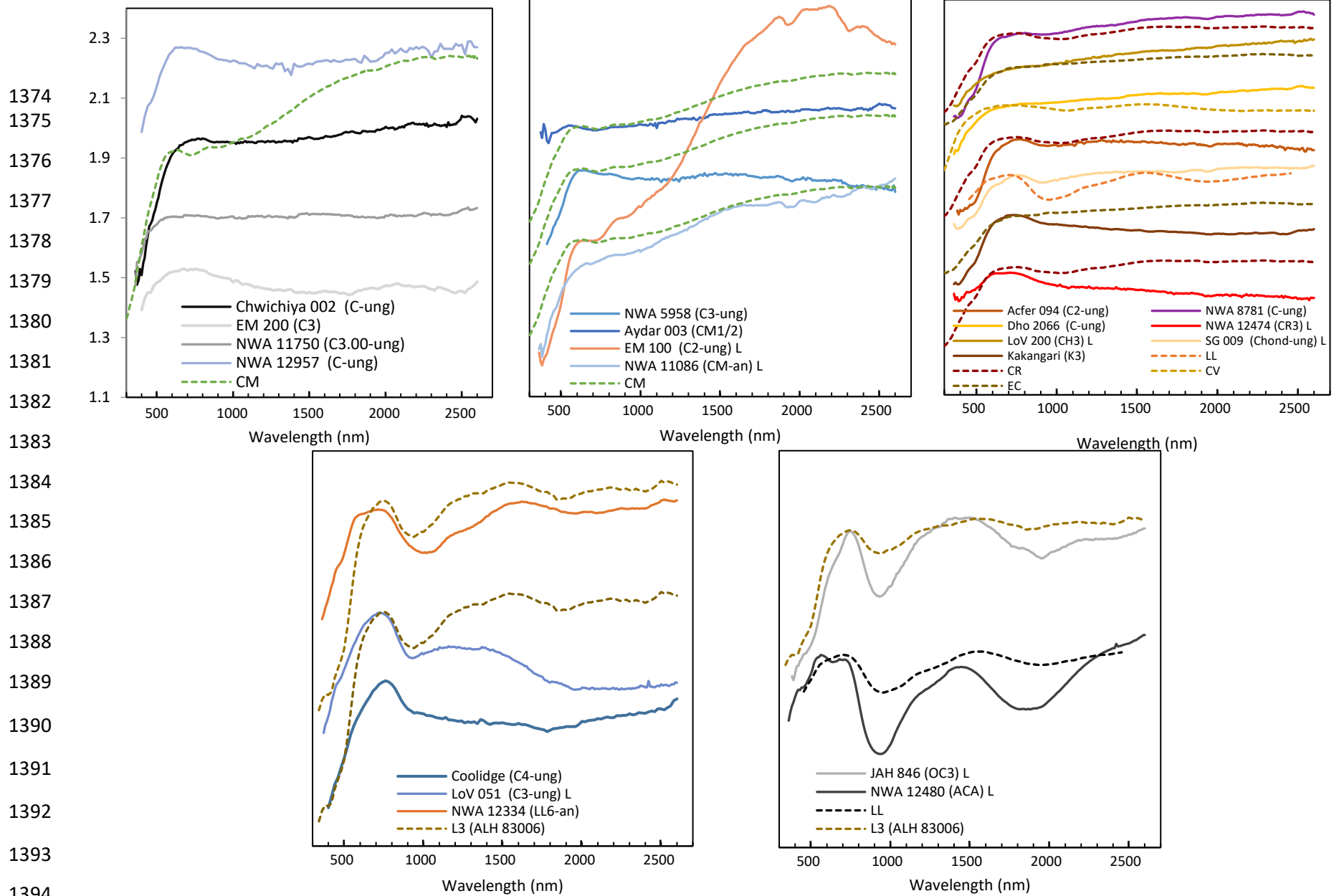


Figure 11: Visible-near-infrared reflectance spectra of studied samples (solid line) compared to spectra of selected groups of meteorites (dashed lines). Spectra were normalized at 0.55 μm and then offset for clarity. Number 1-6 are spectral group of meteorites. No comparison for the spectral group 4 was made, as meteorites in this spectral group belong to the well-established R chondrite group. "L" is for leached powdered samples; ACA : acapulcoite; Chond-ung : chondrite ungrouped..

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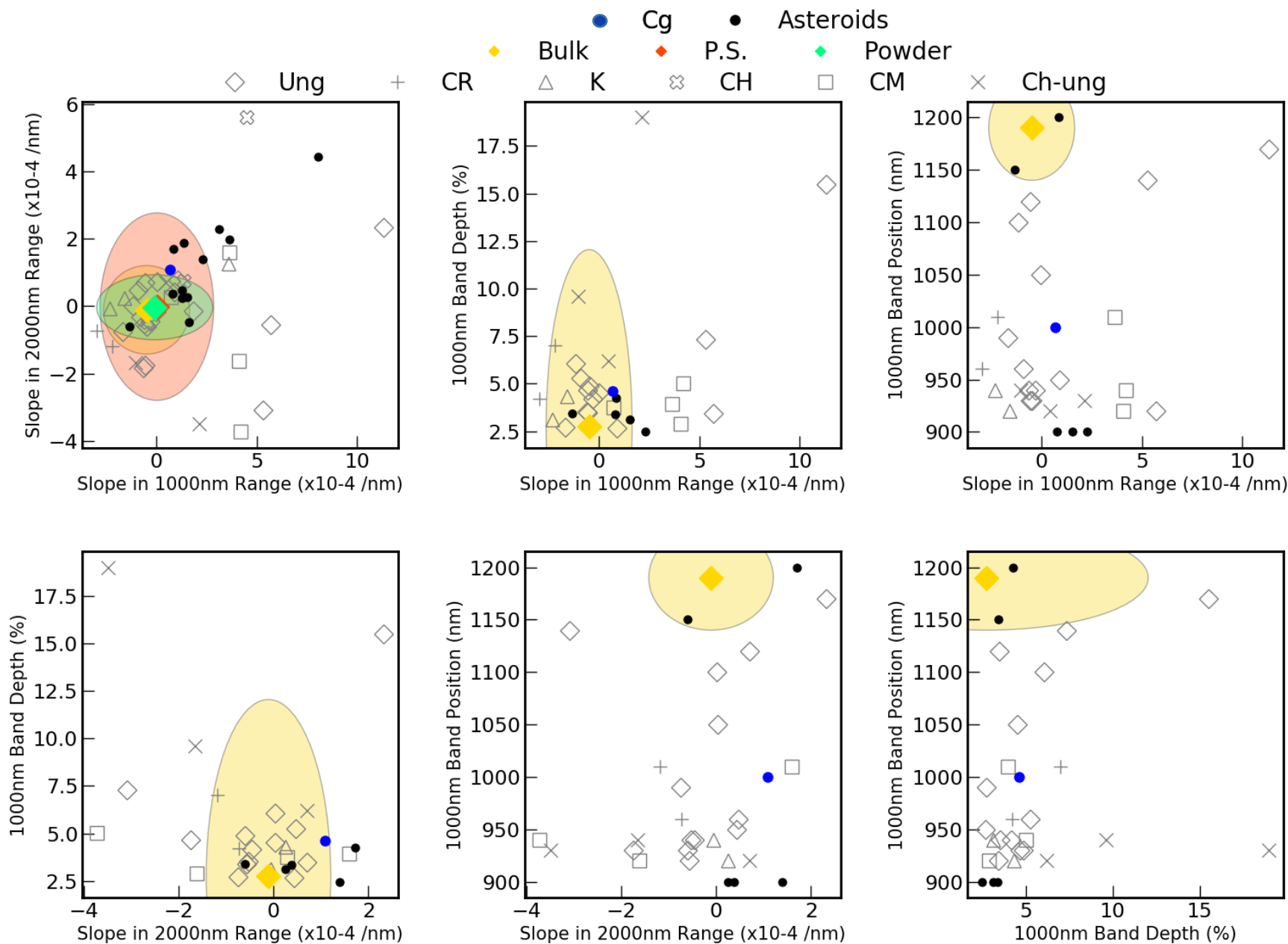


Figure 12: Plots of spectral parameters for NWA 11750 (C3.00-ung), belonging to petrographic group A and spectral group 1. Asteroid Highest Recurrent Match (HRM) is Cg-type. Yellow ellipses correspond to bulk sample spectrum data; Green ellipses correspond to powder sample spectrum data; Red ellipses correspond to polished section spectrum data. Chond-ung : chondrite ungrouped; P.S.: polished section.

● Sr ● Asteroids

◆ Bulk ◆ P.S. ◆ Powder-L

△ R ☆ OC ◇ Ung ○ P.ach. × Chond-ung

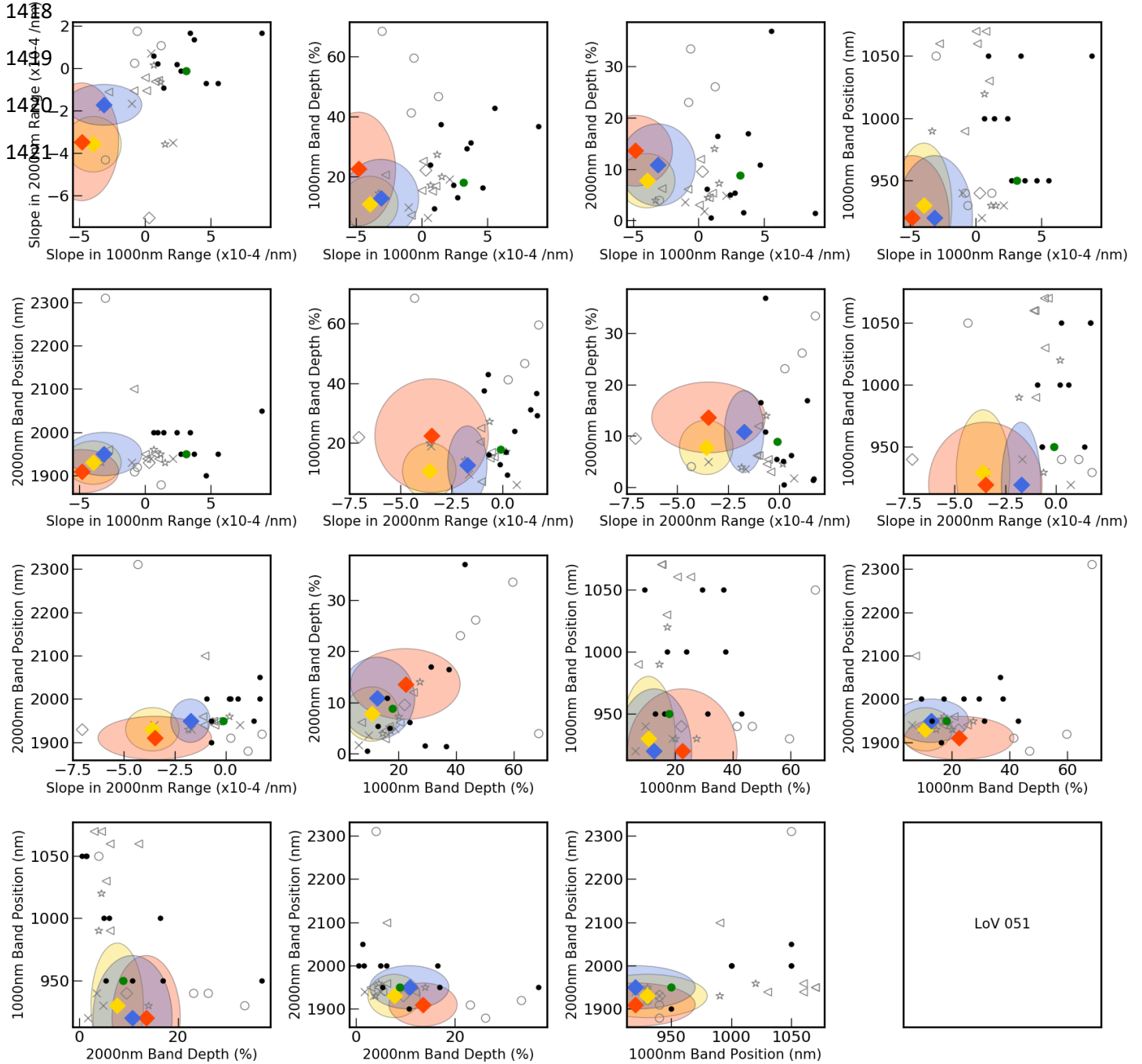


Figure 13: Plots of spectral parameters of LoV 051 (C3-ung), belonging to petrographic group E and spectral group 5. Asteroid Highest Recurrent Match (HRM) is Sr-type. Yellow ellipses correspond to bulk sample spectrum data; Blue ellipses correspond to leached powder sample spectrum data; Red ellipses correspond to polished section spectrum data. Chond-ung : chondrite ungrouped; achondrite-prim : primitive achondrites; P.S.: polished section; Powder-L : powdered leached sample..

Table 1 : Petrographic characteristics of meteorites.

Petro Group	Meteorite	Group	Type	Matrix		Chondrules			Weathering	Fayalite		Ferrosilite (low-Ca Px)		Wollastonite	Plagioclase	Sulfides	Metal	Magnetite	Mag. Susc. (log χ) ($\times 10^{-5}$ /kg)	Ms (Am ² /kg)	
				(vol%)	n	(vol%)	(μ m)	n		(mol%)	n	(mol%)	n								(mol%)
A	Chwichiya 002 ^a	C3.00-ung	3	73.4*	421	12.9*	480±300	29	moderate	37.6±16.7	16	3.1±3.0	4	0.8±3	--	--	4.9*	<1.0*	7.8*	4.38*	3.29*
A	NWA 11750 ^b	C3.00-ung	3.00	74.0	/	26.0	240±170	28	minimal	11.9±17.1	7	3.2±2.2	3	3.8±1.1	--	--	1.9**	--	--	4.03*	2.36*
A	NWA 12957 ^c	C3.00-ung	3	63.3*	667	24.8	300±200	25	low	24.3±20.8	21	8.8±12.7	10	1.5±0.8	--	--	6.6*	1.0*	4.1*	4.44*	6.19*
A	Acfer 094 ^d	C2-ung	2	60.9*	368	34.5*	130±125	82	moderate	0-55.0	/	1-16	/	35.5-46.0	An ₇₀₋₉₈	/	1.4*	0.5*	--	4.62*	11.43*
B	NWA 5958 ^c	C2-ung	2	75.5	/	18.9	180±100	1272	W1	2.2±1.1	7	2.6±2.6*	8*	1.1±0.2*	--	--	1.0-2.0	<1.0	1.2	416*	2.07*
B	Aydar 003 ^e	CM1/2	1	73.5*	401	12.2*	270	/	minimal	1.4-14.9	2	26.3*	7*	1*	--	--	14.0	--	7.5**	3.75*	0.90*
B	EM 100 ^f	C2-ung	2	71.8*	339	21.2*	250	/	moderate	7.3±12.1	23	3.7±2.8	7	0.9±0.1	--	--	5.5*	1.5*	--	3.93*	1.34*
B	NWA 11086 ^g	CM-an		58.0*	471	42.0*	240±120	38	severe	14.2±12.2	13	1.4±0.1	2	1.1±0.1	--	--	2.1*	3.0*	--	3.41*	0.37*
B	EM 200 ^f	C3	3	44.1*	669	35.2*	130±80	/	low	22.7±23.6	39	1.6±0.5	7	0.7±0.4	--	--	7.6*	3.6*	32.6**	5.08*	17.10*
B	NWA 8781 ^b	C-ung		55.2*	458	33.0*	210±60	20	low	1.1-70.1	8	1.0-7.0	3	1.2-0.4	--	--	9.2*	2.6*	--	4.16*	2.18*
C	Kakangari ^h	K3	3	66.8	238 mm ²	22.7	690	119	absent	3.2-9.3	/	3.3-14.3	/	--	--	--	10.5	5.8	--	4.88*	15.10
C	NWA 12474 ^e	CR3	3.1	56.0*	888	29.3*	650±310	40	high	1.9±0.8	5	2.4±0.4	7	1.2±0.4	An _{86.4±2.7} Ab _{13.5±2.8} Or _{0.0±0.1} *	2*	4.6*	2.0*	8.0*	4.69*	11.11*
C	LoV 200 ^g	CH3	3	0*	320	66.3*	50±34*	24	minimal	15.2±13.9	8	13.1±14.0	19	2.1±1.8	--	--	3.8*	20.8*	--	5.40*	63.50*
C	Dho 2066 ^g	C-ung	/	54.3*	602	30.5*	620±280	25	W1	1.7±2.3	10	--	--	--	--	--	13.2*	<1*	1.2*	3.96*	2.67*
C	Sierra Gorda 009 ⁱ	Chondrite-ung	/	0*	406	74.5*	1050±577*	25*	moderate	0.5±0.1	74	1.4±0.4	42	0.9±0.6	An _{32.28-95.04} Ab _{4.96-65.99}	/	8.6*	16.9*	--	5.28*	52.40*
D	Awsserd ^g	R4	4	62.6*	411	26.2*	246±60*	68*	minimal	40.9±1.7	/	12.2	/	44.7	An _{7.7} Ab _{89.4} Or _{3.0} * 3*	3*	10.5*	--	--	3.05*	0.127*
D	NWA 12472 ^e	R3	≥3.2	60.5*	430	27.2*	326±264*	37*	high	37.2±0.1	2	--	--	--	An _{13.8} Ab _{82.0} Or _{4.2} * 6*	6*	12.3*	--	--	3.57*	0.234*
E	Sahara 00177 ^{h,o}	C3/4-ung	3/4	22.7*	449	63.3*	500		moderate	8.0±1.0	/	4.1*	7*	4.4*	An _{79.8} Ab _{18.2} Or _{2.1} * 7*	7*	3.6*	3.6*	--	5.15*	/
E	Coolidge ^k	C4-ung	3.8-4	17.2		67.4	610±680	52	very	14.2±3.0	95	11.2±11.0	49	2.7*	An _{74.8} Ab _{21.6} Or _{3.5}	2	2.6	3.7	0.4	4.94*	/
E	Mulga (west) ^l	C5/6-ung	5/6	/	191	76.4*	/	/	slightly	32.0	/	26	/	/	An ₃₃₋₆₄	/	6.8*	<1.0*	16.2*	/	/
E	LoV 051 ^m	C3-ung	3	25.8*	507	55.4*	940±280		minor	13.7±1.4	31	9.2 ± 3.3	9	1.1±0.6	An _{92.6} Ab _{7.1} Or _{0.1}	/	4.9*	13.8*	--	5.24*	32.30*
E	JaH 846 ^b	OC3	≥3.2	13.5*	622	77.2*	560±380		W2	0.6-38.1	9	1.9-35.2	3	0.5-4.4	An _{10.2} Ab _{86.4} Or _{3.4} * 4*	4*	6.9*	1.9*	--	4.91*	2.30*
F	NWA 12334 ^e	LL6-an	6	19.3*	445	64.9*	--	--	/	34.1±0.3	8	27.5	1	2.4	An _{4.1} Ab _{80.0} Or _{15.9}	1	11.7*	--	4.0*	3.06*	0.13*
F	NWA 12480 ^e	Acapulcoite	--	--	--	--	--	--	minimal	--	--	11.2±0.2	4	2.1±0.3	An _{16.6} Ab _{79.0} Or _{4.4}	2	6.0	12.0	--	5.08*	36.6*
F	NWA 6592 ⁿ	Lodranite	--	--	--	--	--	--	W1	16.0*	2*	6.9*	1*	46.0*	An _{22.2} Ab _{74.5} Or _{3.5} * 5*	5*	0.2	11.2	--	5.70*	/

* : analyses done in this study. Other analyses come from bibliography or the Meteorite Bulletins of the Meteoritical Society.

** : abundance calculated from Ms; -- : not detected; / : no data ; Mag. Susc. : Magnetic Susceptibility; n : number of point for modal abundance, number of chondrules for chondrules sizes, or number of minerals for compositions; Ms: saturation magnetization; Petro group : grouping based on petrographic study.

For weathering some samples use the weathering scale of Wlotzka 1993.

^a: The meteoritical Bulletin, no. 109, *In press*; ^b: Gattacceca et al., 2020b; ^c: Jacquet et al. 2016; ^d: Ebel et al. 2016; Newton et al. 1995; Rochette et al. 2007; Greshake 1997; ^e: Gattacceca et al., 2020c; ^f: Ruzicka et al., 2015; ^g: Gattacceca et al., 2019; ^h: Weisenberg et al. 1996; D.T.Britt and G.J.Consolmagno 2003, Rochette et al. 2008; Graham et al. 1977; Barosh et al. 2020; ⁱ: Ivanova et al., 2020; ^j: Rochette et al. 2007; ^k: McSween and Richardson 1977; Van Schmus 1969; McSween 1977; Kallemeyn 1995; Noguchi 1994; ^l: McSween 1977; Weckwerth et al. 1985, Binns et al. 1977; Ivanova et al. 2010; ^m: Ruzicka et al., 2017; ⁿ: Keil and McCoy 2017; ^o: Russel et al., 2015.

Table 2 : Asteroids matching to meteorites.

Petro group	Spectral group	Meteorite	Classification	Qualitative Match (QM)			Highest Recurrent Match (HRM)						Closest Matching asteroids (CMA)			Bus DeMeo taxonomy			Conclusion
				Powder	Raw	P.S.	Powder	Score	Raw	Score	P.S.	Score	Powder	Raw	P.S.	Powder	Raw	P.S.	
A	1	Chwichiya 002	C3.00-ung	C	B	B	Cg-Cgh-Ch-Xc-Xe	1/1	B	3/6	C-Cg-Cgh-Ch-B-Xc-Xe	1/1	Cg	B	B	Cgh-Cg-Xk-Xn	B	B	B-C-Cg
A	1	NWA 11750	C3-ung	C	**	Xc	Cgh-Ch-B	1/1	B	6/6	**	**	Ch	B-C-Cgh	Ch	B	B	Cgh-Cg-Xk-Xn	B-Ch-Cgh-Cg
A	1	NWA 12957	C-ung	Cg	Cg	--	Cg-Cgh-Ch-B	3/6	Cg	3/6	--	--	B	Cg	--	Cgh-Cg-Xk-Xn	B	--	Cg
B	1	EM 200	C3	C	C	C	Cgh-Ch-B-Xc-Xe	1/1	B-Ch	3/6	C-Cg-Cgh-Ch-Xk-B	3/6	Ch-Cg	Cg	Cg	C-B	B	Ch-Xk-Xn	C-Ch-Cg-B
B	2	Aydar 003	CM1/2	Ch	--	Ch	Cg-Cgh-Ch	3/3	--	--	C-Cg-Cgh-Ch-Xk-B-Cb-Xc-Xe	1/1	B	--	Ch	C-Ch-Xk-Xc-Xe-Xn	--	B	Ch
B	2	EM 100	C2-ung	**	**	--	C	1/6	B	1/6	--	--	C	B	--	A-D	C-Ch-X-Xk-Xe-Xn	--	?
B	2	NWA 11086	CM-an	**	**	**	C-Cg-Xk	3/6	Xk	2/6	Cgh-Ch-Xk	5/6	C-Cg	Ch-Xk	Cgh	K-Xe	**	**	?
B	2	NWA 5958	C2-ung	**	B	--	Ch-Cgh-B	4/6	B	1/6	--	--	B-Ch	**	--	K-Xe	K-Xe	--	Ch-B
A	3	Acfer 094	C2	**	**	**	Ch-Cgh-B	3/6	Ch-B	3/6	Xk-Cgh-Ch	3/6	B-Ch	B-Ch	B-Ch-Cgh	Xe-L	Xe-L	Xe-L	?
C	3	NWA 12474	CR3.1	**	**	--	B	3/6	B	3/6	--	--	B	B	--	B	B	--	?
C	3	Dho 2066	C-ung	Xc	Xe-Xk	Xc	Ch-Cg-Cgh-Xk-Xe-Xc	1/1	Cgh-Ch-B-Xe-Xc	1/1	**	**	Xc	Ch	L	Xk-Xc-Xe-C-Ch-Xn	B	Cgh-Cg-Xk-Xn	Xc-Xe-Xk
C	3	Kakangari	K	**	**	**	Ch-Cgh-B	3/6	Xk-Cgh-Ch-B	3/6	C-Cgh-Xk-Cb-T-X-Xc-Xe	1/1	Cgh	B	T	Xe-L	B	Xe-L	Xe-Xk-Cgh-Ch
C	3	LoV 200	CH3	Xe-Xk	Xe-Xk	Xc	Ch-Cg-Cgh-Xc-Xe	1/1	Xe-B-Ch-L	1/1	**	**	Xc	B	**	Xk-Xc-Xe-C-Ch-Xn	B	A-D	Xe-Xk
B	3	NWA 8781	C-ung	**	**	--	Ch-Cgh-Cg	3/6	Ch	6/6	--	--	Xk	B-Ch	--	Xe-L	Xe-L	--	Xe-Xk
C	3	SG 009	Chond-ung	**	**	**	Xk-Cgh-Ch	6/6	B-Cg	2/6	Xk-Cgh-Ch	2/6	Cg-Ch	B-Cg	Cg-Xk	Xe-L	Xe-L	Sv	Xk-Cg
D	4	Awsserd	R4	K	**	K	K-S	10/15	Sr	6/15	K-S-Sq-Sr-Q	10/15	Sq-K	S-Sa-Sr	S	K-Xe	**	K-Xe	K
D	4	NWA 12472	R3	K	K	K	K-Sr-S	10/15	S	4/15	K-O-S-Sr-Sv	6/15	Sq-K	Q	Q	K-Xe	B	Xe-L	K
E	5	LoV 051	C3-ung	S-Sr-Sv	S-Sr-Sv	S-Sr-Sv	S-Sr	6/15	S-Sr-Sv	6/15	R-Sv	6/15	S-Sv	S	Sv	S	**	S	S-Sr-Sv
E	5	Coolidge	C4-ung	**	--	S-Sr-Sq	S-Sr	6/15-	--	--	K-R-S-Sq	3/15	S	--	R/Sq	C	--	**	S-Sr-Sq
E	5	SaH 00177	C3/4-ung	--	--	S-Sr-Sv	--	--	--	--	S	9/15	--	--	Sr	--	--	**	S-Sr-Sv
F	5	NWA 12334	LL-an	S-Sr	**	--	Q-K-Sq	15/15	S	6/15	--	--	Sq	S	--	K-Xe	B	--	S-Sr-Sq
E	6	JaH 846	OC3	Sq-Sv	Sq-Sv	--	Sr	15/15	S-Sr	10/15	--	--	R	Sr	--	Sv	S	--	S-Sr-Sv
F	6	Mulga (west)	C5/6-ung	--	--	Sa-Sv	--	--	--	--	K-Sq	8/15	--	--	Sq	--	--	--	Sa-Sq
F	6	NWA 12480	Acapulcoite	Sv	Sv	Sv	V-R	3/15	V	5/15	R	5/15	R-V	V	Sv-V	V	V	Vw	V-Sv
F	6	NWA 6592	Lodranite	--	--	Sa	--	--	--	--	Sa-A-K	1/15	--	--	Sa	--	--	X-Xk-Xe-C-Xn	Sa

** : no match; -- : no data; Chond-ung : chondrite ungrouped; P.S.: polished section; Petro group : petrographic group.