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► To cite this version:

van T.H. Phan, Eric Quirico, Pierre Beck, Yann Le Brech, Lora Jovanovic, et al.. Infrared spectroscopy quantification of functional carbon groups in kerogens and coals: A calibration procedure. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* [1994-..], 2021, 259 (October), pp.119853. 10.1016/j.saa.2021.119853 . insu-03208201

HAL Id: insu-03208201

<https://insu.hal.science/insu-03208201v1>

Submitted on 12 Oct 2021

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Infrared spectroscopy quantification of functional carbon groups in kerogens and coals: A calibration procedure

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22 **ABSTRACT**

23 The determination of the abundances of the CH_x, C=O and aromatic groups in chondritic
24 Insoluble Organic Matter (IOM) and coals by Infrared (IR) spectroscopy is a challenging issue,
25 due to insufficient knowledge on the absorption cross-sections and their sensitivity to the
26 molecular environment. Here, we report on a calibration approach based on a ¹³C synthetic
27 model material, whose composition was unambiguously determined by Direct-Pulse/Magic
28 Angle Spinning Nuclear Magnetic Resonance (DP/MAS NMR). Ratios of the cross-sections of
29 the CH_x, C=O and aromatic groups have been determined, and the method has been applied to
30 IOM samples extracted from four chondrites as Orgueil (CI), Murchison (CM), Tagish Lake
31 (C2-ungrouped) and EET 92042 (CR), and to a series of coals. The estimate of the aliphatic to
32 aromatic carbon ratio ($n_{\text{CH}_x}/n_{\text{Aro}}$) in IOM samples from Orgueil, Murchison and Tagish Lake
33 chondrites is in good agreement with Single-Pulse/NMR estimates earlier published, and is
34 lower by a factor 1.3 in the case of the CR chondrite EET 92042 (but error bars overlap). In
35 contrast, the aliphatic to carbonyl ratio ($n_{\text{CH}_x}/n_{\text{C=O}}$) is overestimated for the four chondrites.
36 These discrepancies are likely due to the control of the absorption cross-section of the C=O and
37 C=C bonds by the local molecular environment. Regarding coals, the use of published NMR
38 analyses has brought to light that the integrated cross-section ratio $A_{\text{CH}_x}/A_{\text{Aro}}$ varies with the
39 vitrinite reflectance over an order of magnitude. Here as well, the local oxygen speciation plays
40 a critical control on A_{Aro} , which decreases with increasing the vitrinite reflectance. We provide
41 an analytical law that links $A_{\text{CH}_x}/A_{\text{Aro}}$ and vitrinite reflectance, which will allow the
42 determination of $n_{\text{CH}_x}/n_{\text{Aro}}$ for any coal sample, provided its vitrinite reflectance is known.

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44 **Keywords:** Infrared spectroscopy, Nuclear Magnetic Resonance (NMR), Kerogens, Coals,
45 Insoluble Organic Matter, Chondrites, Composition

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60 1. INTRODUCTION

61 Infra-Red (IR) spectroscopy is a non-destructive technique well suited to characterize
62 complex insoluble organic compounds in meteorites and coals. It provides an estimation of
63 organic composition based on the integrated absorbance of the main functional groups (e.g.,
64 alkyl CH, CH₂ and CH₃, aromatic C=C and C-H, carbonyl/carboxylic C=O, hydroxyl -OH) and
65 tracers of the chemical and structural evolution during diagenesis and catagenesis (Li et al.,
66 2016; Lis et al., 2005a; Painter et al., 1981; Petersen et al., 2008; Sun, 2005; Chen et al., 2012;
67 Xueqiu et al., 2017). In addition, micro-FTIR, and more recently, Atomic force microscopy-
68 based infrared spectroscopy (AFM-IR), has offered new perspectives to collect spatially
69 resolved IR spectra, thereby identifying chemical heterogeneities at the submicrometric scale
70 (Yang et al., 2017; Jakob et al., 2019; Abarghani et al., 2020; Jubb et al., 2020). These techniques
71 have been proved valuable for the characterization of precious extraterrestrial micrometric
72 grains, like Interplanetary Dust Particles (IDPs), Antarctic micro-meteorites and matrix grains
73 extracted from rare primitive chondrites (Battandier et al., 2018; Beck et al., 2010; Dartois et
74 al., 2004; Kebukawa et al., 2018; Mathurin et al., 2019; Orthous-Daunay et al., 2013; Quirico
75 et al., 2018; Quirico et al., 2014). Although the assignment of the main vibration bands has
76 reached a consensus, quantifying the exact proportions of functional groups based on IR signal
77 remains difficult (Painter et al., 1981; delaRosa et al., 1992). Indeed, only a few absorption
78 cross-sections have been published so far (Sandford et al., 1991; Dartois et al., 2004; Russell et
79 al., 2009; Takahama et al., 2013). In addition, due to the complex structure of kerogens and
80 coals, a given chemical group exists within different molecular environments, and is difficult to
81 reside in various frequency shifts, inhomogeneous broadening and variability of the absorption
82 cross-section values (Craddock et al., 2015).

83 Here, we report the determination of the absorption cross-sections of the alkyl (CH_x),
84 carbonyl (C=O) and aromatic (C=C) groups based on a H¹³CO synthetic kerogen analogue
85 (named H¹³CO-tholins), whose composition is unambiguously determined by DP/MAS (Direct
86 Polarization/Magic Angle Spinning) Nuclear Magnetic Resonance and XANES (X-ray
87 Absorption at Near-Edge Spectroscopy) at the C K-edge. The use of a ¹³C sample (e.g.
88 synthesized H¹³CO-tholins) overcomes the critical bias of undetected carbons encountered in
89 solid-state ¹³C NMR analysis. These absorption cross-sections have been applied to a series of
90 infrared spectra of kerogens extracted from primitive chondrites, and to a series of coals ranging
91 a broad range of maturity. As the relative abundances of C=O, C=C and CH_x groups in these
92 samples are reported in several publications, the calibration protocol could be tested, and we
93 further discuss the dependency of the cross-sections with the chemical structure.

94

95 2. MATERIALS AND METHODS

96 2.1 Sample selection and preparation

97 2.1.1 Production of IOM analogues from HCO-tholins

98 HCO-tholins samples are polymeric disordered carbonaceous materials that were
99 synthesized in the PAMPRE experimental reactor located at LATMOS (Guyancourt, France)
100 (Alcouffe et al., 2010; Szopa et al., 2006). This setup consists in a radio-frequency capacitively
101 coupled plasma (RF CCP) confined within a cylindrical cage, filled with an initial gaseous
102 mixture made of 7% of CH₄, 3% of CO and 90% of Ar gas, with a 3 sccm flux under the total
103 pressure of 0.43 mbar. Two types of H¹²CO and H¹³CO tholins were produced from natural ¹²C-
104 rich and ¹³C- rich gases (purity > 99.5%), provided by Eurisotop (Saclay, France). The power
105 delivered by the generator was maintained within 11–12 W. Grains were formed within the
106 plasma and kept under electrostatic levitation, and grew up until they deposited into a glass
107 vessel surrounding the confining cage of the plasma. Experiments were run daily (8-10 h) during
108 working hours for safety. The temperature of the electrode was 21°C when starting the
109 discharge, and 45°C when switching it off in the evening. At total, about 30 mg of H¹³CO-tholins
110 were obtained in 63 hours, and 130 mg of H¹²CO-tholins in 98 hours. The production yield, 0.50
111 to 1.3 mg.hour⁻¹, was much lower compared to tholins formed from N₂ : CH₄ mixtures
112 (Sciamma-O'Brien et al., 2010). The H¹³CO-tholin was composed of a dominant yellow, fine-
113 grained powder and a less abundant population of dark platelets (Fig. S-1). In comparison, the
114 H¹²CO-tholins did not contain any dark grains. The black platelets were constituted by direct
115 deposition on the grid, which eventually fell and mixed with the dusty tholins. Infrared
116 spectroscopy has shown that these two populations were chemically similar (Fig. S-2). Finally,
117 the differences in the color of the grains are probably due to the larger thickness of the platelets.

118 Analogues of kerogens and coals were obtained from the carbonization of H¹³CO-tholins
119 with the elemental composition revealed in Table S-1 (Supporting Information). To select
120 optimal conditions to get the good analogues, preliminary heating experiments were run at 200
121 °C, 300 °C, 350 °C, 400 °C, 450 °C, 500 °C and 550 °C, with a tubular furnace maintained
122 under secondary vacuum (~ 10⁻⁶ mbar). Small grains of samples were selected and pressed
123 between two diamond windows and put into a ceramic crucible that was placed at the middle of
124 the tube. For each experiment, the setting temperature was maintained during 1h, and the tube
125 was then let cool down freely for 3–6 hours, depending on the initial temperature setting.
126 Infrared spectra of the heated samples were collected and compared to spectra of Insoluble
127 Organic Matter (IOM) samples extracted from primitive chondrites (Fig. S-2). Finally, we select
128 a temperature of 400°C (for extensive details on the procedure, see Supporting Information).
129 The final carbonization of HCO-tholins was then operated with this set temperature, using a
130 ceramic crucible filled with 5–10 mg of the powdered samples. We used an anti-static gun
131 (Zerostat, Sigma-Aldrich) to limit sample loss due to static electricity.

132

133 **2.1.2 Coal and IOM samples**

134 A suite of coal samples with a mean maximum vitrinite reflectance (R_o) ranging 0.33–
135 2.8% were purchased from the Penn State University coal sample Bank
136 (<http://www.energy.psu.edu>) (Table S-2). The IR spectra of IOMs extracted from primitive
137 chondrites have been earlier published in Orthous-Daunay et al. (2013), including IOMs from
138 Orgueil (CI1), Murchison (CM2), EET92042 (CR2) and Tagish Lake (C2-ung), while the IR
139 spectra of coals were collected by using Bruker Vertex 70v spectrometer.

140

141 **2.2 Analytical methods**

142 **2.2.1 FTIR measurements**

143 The FTIR instrument used was a Bruker Hyperion 3000 infrared microscope, equipped
144 with liquid nitrogen cooled–mercury cadmium telluride (MCT) detector. *Micro*-FTIR spectra
145 were collected in the range of 4000 – 700 cm^{-1} with a spectral resolution of 4 cm^{-1} . No samples
146 required more than 200 scans (5 min) to get a satisfying signal-to-noise ratio. All measurements
147 were done using an environmental cell with an optical path through two ZnS windows and
148 pumped to $\sim 10^{-6}$ mbar (Beck et al., 2010). The sample (e.g., tholins, coal) was deposited onto
149 a type IIa synthetic diamond window (3 mm diameter, 500 μm thick) and crushed with a similar
150 window to have a thin and flat sample. The diamond window holding the crushed sample was
151 inserted in the cell, pumped, and the window was heated at 80 $^{\circ}\text{C}$ to remove efficiently adsorbed
152 water. Background spectra were collected on a location next to the sample just before measuring
153 the sample.

154 FTIR spectra of bulk coals and HCO-tholins samples were collected on KBr pellets.
155 Pellets were prepared using 300 mg of a KBr powder previously heated at 300 $^{\circ}\text{C}$ under vacuum
156 during 3 h. The sample (1 ± 0.1 mg) was ground and mixed with 300 mg KBr with a MM200
157 Retsch grinder equipped with an agate mortar filled with a single ball (30 Hz; 30 minutes).
158 Finally, 13 mm diameter pellets were prepared using a press AtlasTM Manuelles (Eurolabo),
159 under 400 bars and the gentle heating at 60 $^{\circ}\text{C}$ during 1h (cooling down during 30 minutes).
160 Infrared spectra were collected under vacuum condition with a Bruker Vertex 70v spectrometer,
161 in the range 4000 – 400 cm^{-1} with 200 scans and a 4 cm^{-1} spectral resolution.

162

163 **2.2.2 Solid-state Nuclear Magnetic Resonance**

164 The H^{13}CO - tholins material was characterized by solid NMR using an AVANCE 750
165 MHz wide-bore spectrometer (BrukerTM) operating at MAS rate of 60 kHz designed for 1.3 mm
166 outside diameter (OD) zirconia rotors (closed with vespel caps). About 1 – 5 mg of materials
167 was put inside the rotor. Under those conditions (188.62 MHz and 60kHz spinning speed), any
168 rotational sideband was thrown out of the spectral region of interest. This allows a proper
169 deconvolution of spectra. Proton decoupling during acquisition was obtained by using SPINAL-
170 64 at a 200 kHz ^1H RF field (Fung et al., 2000). All spectra were collected within a 250kHz
171 spectral windows (1325.3ppm) and 16324 acquisition time domains. To get undistorted
172 lineshapes and filter out background probes signal, the quantitative Direct Polarization (DP) was
173 performed using a speed synchronized spin-echo (Hahn, 1950; Vieira et al., 2016; Lucherelli et
174 al., 2019), pulse sequence $\text{P}_{90^{\circ}}\text{-}\tau\text{-P}_{180^{\circ}}\text{-}\tau$, with the following conditions: 2.75 μs and 5.5 $^{\circ}$ s for $\text{P}_{90^{\circ}}$
175 and $\text{P}_{180^{\circ}}$ pulses, and echo time being set to 33.6 μs (2 rotation periods). Under such conditions,
176 baseline problems and first order phasing are fixed, which is a prerequisite for quantitative
177 analysis. T1 (spin-lattice relaxation time) were measured following inversion-recovery method
178 (Kingsley, 1999) and led us to set up DP experiments with recycling delays equal to 30s. NMR
179 spectra were processed with the Topspin software (phase and baseline, LB=25 applied). The
180 interpretation of 1D ^{13}C NMR spectra presents a significant difficulty due to signal overlap.

181 Therefore, the spectral decomposition of the spectra was performed with the DMFIT Software
182 developed by Massiot et al. (2002) and previously used for biomass and biochar using Gaussian
183 profiles (Le Brech et al., 2016). The decomposition was repeated three times for the 400 °C
184 H¹³CO- tholins to estimate the uncertainty on the derived composition due to the processing.

185

186 2.2.3 STXM-XANES analysis

187 Synchrotron-based scanning transmission X-ray microscope (STXM) analyses were
188 performed on heated H¹²CO- and H¹³CO-tholins to document the carbon speciation using the
189 HERMES STXM beamline at the synchrotron SOLEIL (Saint-Aubin, France) (Belkhou et al.,
190 2015; Swaraj et al., 2017). Samples were prepared either by cryo-ultramicrotomy (H¹³CO-
191 tholins) or by depositing the powder on a Si₃N₄ membrane (H¹²CO-tholin). Energy calibration
192 was done using the well-resolved 3p Rydberg peak of gaseous CO₂ at 294.96 eV (Swaraj et al.,
193 2017). XANES hypercube data (stacks) over the carbon absorption range (250 – 350 eV) were
194 collected with a spatial resolution of 35 nm at energy increments of 0.1 eV over the 283 – 291.5
195 eV region, with a dwell time of less than 1 ms per pixel to prevent irradiation damage (Wang et
196 al., 2009). Stack alignments and extraction of XANES spectra were done using the aXis2000
197 software (ver2.1n). Normalization of data and quantification of the concentrations of functional
198 groups were done using the QUANTORXS freeware
199 (<https://github.com/CorentinLG/QuantORXS/>) described in Le Guillou et al. (2018). Note that
200 although this quantification procedure provides consistent results for aromatic, ketone\phenol
201 and carboxylic\ester groups, it remains difficult to estimate the concentration of aliphatic groups
202 precisely.

203

204 2.2.4 Raman setup

205 Raman measurements were collected with a HORIBA JOBIN-YVON LaRam
206 spectrometer, equipped with a 600 gr.mm⁻¹ groove and operating at 532 nm (INSU national
207 Facility at ENS-Lyon, France). The laser beam was focused through a ×100 objective. The
208 power onto the sample was 380 μW, and acquisition time was 5×20s. The configuration used
209 yields a lateral resolution of ≈ 1 μm.

210

211 2.2.5 Analysis of infrared spectra

212 For each spectrum, a baseline correction was done using spline functions, and the peak
213 absorbance of the C=C band at 1540 cm⁻¹ was set to 1. The C=O and C=C bands in H¹³CO-
214 tholin spectra at 1656 and 1540 cm⁻¹, respectively, were fitted with Gaussian profiles (using the
215 multi-fit peak functions of the Igor 8 software, Wavemetrics) (Fig.1).

216 The integrated cross-section is defined by:

217
$$A = \int_{\nu_1}^{\nu_2} \sigma d\nu = \int_{\nu_1}^{\nu_2} \ln(10) \frac{a(\nu) \times S}{n} d\nu \text{ (cm/group) (Equation 1)}$$

218 where $a(\nu) = -\log(\frac{I}{I_0})$ is the absorbance, with I and I_0 are the intensity of the infrared beam
219 after and before the sample, respectively; n is the number of molecular oscillators and σ is the
220 absorption cross-section (cm^2), with ν the wavenumber, ν_1 and ν_2 the edges of the spectral range
221 of the spectral component, and S is the probed area (cm^2).

222 Finally, the ratio of the absorption cross-section of two chemical groups X_1 and X_2 is:

223
$$\frac{A_{X1}}{A_{X2}} = \frac{a_{X1}}{a_{X2}} \times \frac{n_{X2}}{n_{X1}} \quad (\text{Equation 2})$$

224 where a_X refers to the integrated absorbance of a chemical group X as aliphatic CH_x , $\text{C}=\text{O}$
225 or aromatic species (Aro). a_{CH_x} was calculated from the integration of the alkyl band between
226 2750 and 3000 cm^{-1} , while a_{CO} and a_{Aro} were obtained from a Gaussian fit of the bands at 1656
227 and 1540 cm^{-1} , respectively. The integrated cross-section ratios of the CH_x , $\text{C}=\text{O}$ and Aro
228 molecular oscillators, $A_{\text{CH}_x}/A_{\text{Aro}}$, $A_{\text{CH}_x}/A_{\text{C}=\text{O}}$ or $A_{\text{Aro}}/A_{\text{C}=\text{O}}$ were finally calculated
229 with Equation 2, using estimates from NMR measurements on the 400 °C H^{13}CO -tholin. No
230 estimation of individual A_X cross-sections was made, because NMR measurements provided
231 ratios of chemical groups abundances.

232 Strictly speaking, IR spectroscopy probes normal modes and not bonds. In the case of the
233 CH_x groups, the mass difference between H and C atoms is large and decouples their respective
234 motions. Thus, the corresponding bands are controlled by hydrogen vibration around a single
235 carbon atom. For the terminating carbonyl group, environmental effects from neighboring
236 chemical groups are present, leading to a moderate frequency shift and variations of the
237 absorption coefficient by up to a factor of 2. But for both CH_x and $\text{C}=\text{O}$, the number of bonds
238 or molecular groups is equal to the number of carbon atoms and a straightforward comparison
239 with ^{13}C -NMR is possible. Things get harder in the case of aromatic species. A benzene single
240 ring (C_6H_6), in the gas or as a molecular crystal has a vibration mode at $\sim 1500 \text{ cm}^{-1}$ that involves
241 all carbon atoms (6). Small polycyclic hydrocarbons (1-4 rings) display a sharp narrow band in
242 the range 1700-1500 cm^{-1} , but the number of $\text{C}\cdots\text{C}$ bonds does not equal the number of C atoms.
243 For instance, naphthalene units have 10 C atoms and 11 $\text{C}\cdots\text{C}$ bonds, anthracene and
244 phenanthrene have 14 C atoms and 16 $\text{C}\cdots\text{C}$ bonds, and pyrene 16 C atoms and 19 $\text{C}\cdots\text{C}$ bonds.
245 In the case of larger polycyclic aromatics, theoretical calculations point to a broad feature
246 peaking around 1600 cm^{-1} , which is due to the E_{2g} normal mode that involves all carbon atoms
247 and phonon propagation (Mapelli et al., 1999). Immature kerogens and coals contain small (1-
248 4 rings) polycyclic aromatics inserted in a macromolecular network and display a similar broad
249 band at 1600 cm^{-1} . Altogether, the infrared absorption at 1600 cm^{-1} results from the motion of
250 all carbon atoms, but in contrast no clear connection can be established with a number of $\text{C}=\text{C}$
251 bonds, nor a number of rings. In this respect, the terms “aromatic ring stretch” or “ $\text{C}=\text{C}$ ” used
252 in literature are somewhat misleading, and we have used the term “Aro”. As such, A_{Aro} is
253 controlled by the number of carbon atoms, allowing a direct comparison with ^{13}C -NMR. In the
254 details, we expect significant variations of A_{Aro} with the size and local environment of the
255 polyaromatic specie, for instance $-\text{OH}$ groups (see discussion below).

256 Last, the Artificial Bees algorithm was used from the ESA Package PYGMO
257 (<https://esa.github.io/pygmo/>) and tested two fit models: one based on 7 Gaussian and one on 7

258 pseudo-Voigt components. Each group comprised 50 simulations and the fit quality was
259 estimated with a χ^2 function. A 20000 bees' population over 50 generations was used. For each
260 of the 200 numerical simulations to get the good fit in term of χ^2 value.

261

262 3 RESULTS

263 3.1 Solid-state ^{13}C DP/MAS NMR analysis

264 Solid-state ^{13}C DP/MAS NMR spectra of the pristine and heated H^{13}CO -tholins are
265 presented in Fig. 2a and the band assignment is given in Table 1, following the fitting results in
266 Fig. 2b and 1c for the initial and 400 °C H^{13}CO tholins, respectively. We observe two intense
267 features at 100–160 ppm and 0 – 100 ppm in the spectra of both samples, which are assigned to
268 sp^2 and sp^3 carbon atoms, respectively. The range 0–45 ppm usually points to C atoms in alkyl
269 chains, while the range of 45-90 ppm points to oxygenated aliphatic carbons, e.g. alcoholic,
270 carboxylic or ether groups (Pretsch et al., 2000). It is, however, challenging to separate the
271 respective contribution of these two groups of carbon atoms accurately. sp^2 carbons in the 100-
272 160 ppm range can be assigned to olefinic chains (conjugated and unconjugated alkenes) and
273 aromatic or polyaromatic species. We cannot distinguish these two types of speciation. The
274 broad and weak signal which peaks at 170 ppm points to C=O groups in esters or carboxylic
275 groups, and that at 210 ppm indicates to C=O in ketones or aldehydes. The effect of heating
276 results in a steady increase of unsaturated versus saturated carbons, and a dramatic drop of labile
277 oxygenated groups (Fig. 2a). This is in full agreement with the carbonization process that
278 promotes hydrogen loss, carbonyl loss and aromatization.

279 The relative abundances F_x , of the different carbon groups, was derived through a
280 decomposition procedure using a fit model based on Gaussian components (Fig. b-c; Table 1)
281 (Massiot et al., 2002, Le Brech et al., 2016). The unheated H^{13}CO - tholins appears to be mainly
282 composed of $-\text{CH}_x$ ($x=1$ to 3) groups ($F_{\text{ali}} = \sim 61$ %), olefinic carbons ($F_{\text{aro}} = \sim 32.5$ %) and a
283 lower content of C=O groups ($F_{\text{CO}} = 5.1$ %). The ^{13}C NMR spectrum of the 400 °C heated
284 H^{13}CO -tholins is dominated by aromatic carbons ($F_{\text{aro}} = \sim 64\%$) and contains less aliphatic-CH
285 groups ($F_{\text{ali}} = \sim 32\%$) and C=O groups ($F_{\text{CO}} = 4.1$ %) (Table 1).

286

287 3.2 Raman Analysis

288 The Raman spectrum of the unheated H^{13}CO -tholin is dominated by a strong
289 fluorescence background, with no detectable vibrational bands. The spectra of the heated
290 H^{13}CO -tholin display the first-order carbon bands superimposed onto a high fluorescence
291 background. The spectral contrast (i.e. the intensity of the G and D bands with respect to the
292 fluorescence intensity) is low, leading to poor quality of the reduced spectra after subtraction of
293 a linear baseline (Fig. S-3). The use of a Lorentzian-Breit-Wigner-Fano fit model was
294 complicated, due to the poor spectral quality at the edge of the G and D bands. Despite these
295 troubles, these data point a G band peak position at ~ 1537 cm^{-1} and a FWHM of ~ 80 cm^{-1} . For
296 comparison with published data, the peak position of a ^{12}C -bearing sample can be estimated
297 through $\omega_{12}=\omega_{13}(\mu_{12}/\mu_{13})$, with ω the peak position and μ the reduced mass. We obtain $\omega_{12}=1593$
298 cm^{-1} , which points to a nano-graphitic structure in terms of sp^2 structure and is entirely consistent

299 with a kerogen structure as found in chondritic IOM, coals and terrestrial kerogens (Ferrari &
300 Robertson, 2001; Quirico et al., 2018). These data support that most of the unsaturated carbon
301 atoms are present in small-sized polyaromatic units, with negligible olefinic carbon bonds.

302

303 3.3 XANES analysis

304 STXM-based XANES data revealed that the H¹³CO-tholins heated at 400 °C is
305 homogeneous at the submicrometric level. The prominent feature at 285 – 285.5 eV of the
306 XANES spectra indicate that more than half of the carbon atoms (56%) are involved in
307 aromatic/olefinic groups (C=C groups) (Fig. 3a, Table 2). A shoulder is observed at 287.7 eV,
308 which can be assigned to the aliphatic carbons (-CH_x) (~ 30% of the C atoms). Additional broad
309 features at 286.2 eV and 288.5 eV are assigned to ketone/phenols (C=O and C_{Ar}-OH, ~ 14 % of
310 the C atoms) and carboxylic/ester (R-COOH,R'; ~ 4 % of the C atoms). These estimates are
311 consistent with NMR results. The absorption around 286.5 eV could also be assigned to the
312 nitrile functional group, but its presence is discarded by the low elemental N/C ratio (0.01)
313 (Table S-1). Even if our measurements do not report such heterogeneity in H¹³CO-tholins, we
314 cannot exclude the presence of such tiny inclusions.

315 To validate their XANES quantification method, Le Guillou et al. (2018) applied both
316 XANES and DP/MAS NMR techniques to fresh lignin and lignin heated at 300 °C and 350 °C
317 given by Le Brech et al. (2016). This work suggested that XANES and NMR quantification
318 methods provide consistent results for aromatic groups, ketone/phenol groups and
319 carboxylic/ester groups. However, the aliphatic groups of lignin samples appeared
320 overestimated by about 15%. In the case of the heated H¹³CO-tholins, there is a reasonable
321 agreement between XANES and NMR for the aliphatic and the carboxylic groups (Fig. 3b). In
322 contrast, the aromatic groups' abundances determined from XANES are lower than that obtained
323 from DP/MAS NMR, as 55 ± 4 % and 64 ± 1 %, respectively.

324

325 3.4 Infrared spectroscopy

326 The infrared spectra of the initial and 400 °C H¹²CO and H¹³CO-tholins are presented in
327 Fig. 4. The heterogeneity of the 400 °C H¹³CO-tholins was checked in both the KBr pellet and
328 Micro-FTIR spectra (Supporting Information, Fig. S-4). The broadband at 3600 – 3100 cm⁻¹
329 corresponds to the stretching mode of – OH groups in alcohols, carboxylic groups or phenol
330 (C_{aro}-OH). The peak at 3100 – 3000 cm⁻¹ is assigned to aromatic C-H. The region of 2800–3000
331 cm⁻¹ displays four main peaks, including the antisymmetric and symmetric stretching modes of
332 methyl (CH₃) and methylene (CH₂) groups and possibly of the CH group, as a component
333 centered at ~ 2900 cm⁻¹. However, this spectral range is highly congested and more components
334 are present (see below). The spectral region 1800 – 1500 cm⁻¹ displays bands at 1656 and 1540
335 cm⁻¹, and 1708 cm⁻¹ and 1608 cm⁻¹ for the H¹³CO and H¹²CO-tholins, respectively. These
336 features (e.g., 1656 and 1540 cm⁻¹) are assigned to the stretching modes of the carbonyl (C=O)
337 and aromatic (C=C), respectively (Painter et al., 1981). In the region 1500 – 900 cm⁻¹, bending,
338 deformation and out-of-plane modes of CH₂, CH₃ and C-O bonds are present at 1450, 1375 and
339 1300 cm⁻¹. We will follow here Painter et al. (1981) which state that the broad feature peaking

340 at $\sim 1200\text{ cm}^{-1}$ does not provide any significant compositional information, in particular on the
341 abundance of ether groups (-C-O-C-).

342

343 **3.4.1 Spectral decomposition of the CH_x stretching region**

344 The region between $3000 - 2750\text{ cm}^{-1}$ results from the contribution of symmetric and
345 antisymmetric stretching modes of CH_2 , CH_3 , possibly of -CH, and contains information on the
346 abundance of alkyl groups and the ratio of CH_2 and CH_3 groups. However, the spectral
347 congestion makes it difficult to identify the exact number of components, spectral profiles and
348 physical interpretation. Pure alkanes at a low temperature usually display several components
349 ascribed to the d^- antisymmetric stretch of chain CH_2 , the symmetric stretch of terminal CH_2
350 ($d^+\omega$) and two components arising from a Fermi resonance between the symmetric stretch of
351 chain CH_2 and the overtone of the H-C-H bending mode, reported as d^+ and d^+_{FR} (the first being
352 dominating by the fundamental mode) (Fig. 5) (MacPhail et al., 1984); other components are
353 the r_a and r_b in-plane and out-of-plane asymmetric stretch of $-\text{CH}_3$, and the symmetric stretch
354 in Fermi resonance with the first overtone of the CH_3 bending mode, named r^+ and r^+_{FR} . Pure
355 alkanes measured at low-temperature display peaks and shoulders in agreement with this
356 assignment. However, the different components cannot be guessed for a similar compound in
357 the liquid state at room temperature (Fig. 5). Even more, critical issues arise in the case of natural
358 complex mixtures or solids, such as broader components, spectral shapes changes and peak
359 position shifts. In the case of coals and chondritic IOM, the presence of oxygen as ether or
360 carbonyl groups likely modifies the spectral distribution, making uncertain the spectral
361 decomposition of the bands (Orthous-Daunay et al., 2013; Quirico et al., 2018).

362 To explore more quantitatively this congestion issue, we ran optimization simulations of
363 the fit of the alkyl band of an IOM sample extracted from the Orgueil (CI1) chondrite (Orthous-
364 Daunay et al., 2013). We used the Artificial Bees algorithm from the ESA Package PYGMO
365 (<https://esa.github.io/pygmo/>) and tested two fit models: one based on 7 Gaussian and one on
366 seven pseudo-Voigt components. Two components aimed to fit the small features at ~ 3000 and
367 2790 cm^{-1} , due to the aromatic C-H stretch and a combination mode from fundamental modes
368 in the fingerprint region (Fig. 6). The fit model of the aliphatic bands then consisted of five
369 components, as usually reported in the literature (Dartois et al., 2007, 2004; Orthous-Daunay et
370 al., 2013). We ran two groups of simulations: one keeping constant the Full Width at Half
371 Maximum FWHM of 35 cm^{-1} for all the components, and another one where FWHM is let free
372 within the range $20\text{-}40\text{ cm}^{-1}$. Each group comprised 50 simulations, and the fit quality was
373 estimated with a χ^2 function. A 20000 bees' population over 50 generations were used. For each
374 of the 200 numerical simulations, the resulting fit was excellent in terms of χ^2 value (Fig. 6a).
375 The results are summarized in Fig. 6b-c. Two parameters are of particular interest: (1) the ratio
376 of the integrated absorbance of the antisymmetric stretching components of CH_2 and CH_3
377 ($a_{\text{CH}_2}/a_{\text{CH}_3}$) and (2) the sum of these values. The first estimates the ratio of the number of CH_2
378 over CH_3 groups, while the second is a measure of the alkyl content ($a_{\text{CH}_2}+a_{\text{CH}_3}$). Note, however,
379 that for this latter the abundance of the CH group is not measured regarding the assignment of
380 the central component peaking at $\sim 2900\text{ cm}^{-1}$ to the overtone of a bending mode in Fermi
381 resonance with a fundamental C-H stretch (Dartois et al., 2007; 2004). In the case of FWHM

382 forced to 35 cm^{-1} , we obtain 1.36 ± 0.07 and 1.52 ± 0.28 for $a_{\text{CH}_2}/a_{\text{CH}_3}$ and 57.0 ± 1.8 and 59.0
383 ± 2.7 for $a_{\text{CH}_2+a_{\text{CH}_3}}$, for the Gaussian and pseudo-Voigt models, respectively (Fig. 6b). If FWHM
384 is let free within $20\text{--}40\text{ cm}^{-1}$, we obtain 1.37 ± 0.79 and 1.66 ± 0.90 for $a_{\text{CH}_2}/a_{\text{CH}_3}$ and 50.4 ± 6.3
385 and 52.8 ± 7 for $a_{\text{CH}_2+a_{\text{CH}_3}}$, for the Gaussian and pseudo-Voigt models, respectively. The
386 dispersion is much larger, and the absolute values of the sum are also significantly different
387 from those obtained by forcing FWHM. To make things clear on the impact in terms of chemical
388 information, we can estimate the $n_{\text{CH}_2}/n_{\text{CH}_3}$ of Orgueil IOM, using the A_{CH_2} and A_{CH_3} values
389 from [Dartois et al. \(2007\)](#). We find that $n_{\text{CH}_2}/n_{\text{CH}_3}$ ranges between 0.5 and 4.5, while NMR
390 measurements provide a value ranging 1.9-2.6 ([Gardinier et al. 2000](#); assuming that ether
391 bridges are $\text{CH}_3\text{-O-CH}_2\text{:CH}_2\text{-O-CH}_2=1:1$ or $\text{CH}_2\text{-O-CH}_2$, respectively). This result is basically
392 of little value. In practice, things may not be as worse, provided that the fit model is similar to
393 that used to derive the absorption cross-sections. Finally, due to the sensitivity of the fit models
394 on derived parameters, and to propose an easy procedure allowing cross-comparison of data
395 collected by independent groups, we prefer to use the integrated absorbance of the whole alkyl
396 band, in place of $a_{\text{CH}_2+a_{\text{CH}_3}}$. The calibration presented below will lose accuracy when the
397 $n_{\text{CH}_2}/n_{\text{CH}_3}$ ratio departs from that of the alkane's standards, but as discussed below, the impact
398 is very limited.

399

400 **3.4.2 Determining the $CH_x/A_{C=C}$ and $A_{CH_x}/A_{C=O}$ ratios**

401 The ratio of the absorption cross-section of two chemical groups X_1 and X_2 is calculated
402 from the Equation 1. The term n_{X_2}/n_{X_1} is provided by the NMR analysis, and the integrated
403 absorbances of the alkyl, carbonyl and aromatic groups are measured in the spectra of the 400
404 $^\circ\text{C H}^{13}\text{CO}$ -tholins. The uncertainty values were estimated by considering fit uncertainties, the
405 baseline correction, sample heterogeneity (Fig. S-4) and the uncertainty on NMR values of the
406 relative abundance of the three chemical groups. We finally obtain the ratio values of integrated
407 cross-section: $A_{\text{CH}_x}/A_{\text{Aro}} = 1.578 \pm 0.183$ and $A_{\text{CH}_x}/A_{\text{C=O}} = 0.116 \pm 0.006$ (Table 3).

408

409 **4 DISCUSSION**

410 **4.1 Achievements and limitations**

411 The composition of the H^{13}CO -tholin determined by NMR is very reliable for the
412 aliphatic and aromatic contents, due to intense DP/MAS features at 38 and 130 ppm that are
413 unambiguously assigned to alkyl and conjugated carbons. Unlike CP/MAS data, these spectra
414 do not suffer from selective signal enhancement and are suitable for quantification. The
415 assignment is also robust for oxygen-bearing groups, but the features at 169 and 200 ppm are
416 weak and suffer from a higher uncertainty in their relative abundances. The new calibration of
417 H^{13}CO -tholin allows determining the absorption cross-section ratios of the CH_x , C=O and Aro
418 groups.

419 Nevertheless, the calibration derived from the H^{13}CO -tholins suffers from limitations
420 and biases that are intrinsic to infrared spectroscopy. First, as we estimate the alkyl abundance
421 through the integration of all the alkyl bands (CH_x stretching in the range of $3000\text{--}2800\text{ cm}^{-1}$),

422 the validity of the H¹³CO-tholins as a calibration standard relies on a similar distribution of the
 423 alkyl groups in the kerogen and coal samples that are analyzed. Hence, the absorption cross-
 424 section of CH₂ and CH₃ are not identical, e.g. for the anti-symmetric stretching modes A_{CH₃} =
 425 (11.8 ± 0.76) × 10⁻¹⁸ and A_{CH₂} = (7.7 ± 1.5) × 10⁻¹⁸ cm/group (Dartois et al., 2007; Sandford et
 426 al., 1991). Considering a variation range of 1.5 – 3.0 for n_{CH₂}/n_{CH₃} that is observed in chondritic
 427 IOM (Orthous-Daunay et al., 2013), we can calculate the variation of the sum of the integrated
 428 absorbance of the anti-symmetric stretching modes of CH₂ and CH₃, a=a_{CH₂}+a_{CH₃}, as:

$$429 \quad \frac{a_{1.5}}{a_3} = \frac{1 + \frac{1}{1.5} \frac{A_{CH_3}}{A_{CH_2}}}{1 + \frac{1}{3} \frac{A_{CH_3}}{A_{CH_2}}} = 1.18$$

430 This means that n_{CH₂}/n_{CH₃} estimates on IOM from thermally processed chondrites
 431 obtained with our calibration are underestimated by 20% at maximum. Second, a critical issue
 432 with the 1600 cm⁻¹ band is the sensitivity of its absorption cross-section to the oxygen molecular
 433 environment, in particular the phenolic (-OH) and possibly the ether (C-O-C) groups (Painter et
 434 al., 1981). This means that the kerogen to be analyzed should be as similar as possible to the
 435 calibration standard in terms of oxygen speciation around aromatic carbons. In this respect, the
 436 400°C H¹³CO-tholins do not fit mature samples that have large polyaromatic units, and which
 437 are known to have a lower aromatic cross-section. This issue is probably more critical for coals,
 438 due to the large O/C variations upon maturity.

439

440 4.2 IOM composition of primitive chondrites

441 A way to test our calibration is to apply our method to samples whose composition has
 442 been previously determined by NMR. We report here the composition (n_{CH_x}/n_{C=O} and n_{CH_x}/n_{C=C})
 443 of the IOMs from the Orgueil, Murchison, EET 92042 and Tagish Lake chondrites, derived
 444 from the spectra published by Orthous-Daunay et al. (2013) (Fig. S-5). These compositions are
 445 compared with the NMR estimates of Cody & Alexander, (2005) and Gardinier et al. (2000)
 446 (Fig. 7). It is first necessary to discuss those NMR data, which display some inconsistencies
 447 between them.

448 Two types of NMR measurements are presented in these publications: Single-pulse (SP)
 449 MAS and Cross Polarized (CP) MAS. Single-pulse (SP) MAS NMR is usually presented as
 450 suitable for quantification (Baccile et al., 2014), but in the case of natural samples (¹³C/¹²C ~
 451 1%), the signal is low, long acquisition time is required, and eventually the spectra still contain
 452 significant noise. In the case of broad features, band distortion can happen due to dephasing
 453 processes before spectrum acquisition, leading to significant errors in the quantification of band
 454 integral. In addition, the baseline may depart from an ideal flat line, thereby perturbing the
 455 profile of broad features. Altogether, these artifacts may lead to significant errors. These issues
 456 can be fixed, at least partly, by using spin echo DP/MAS experimental configuration, as done
 457 here on the standard samples. By applying two subsequent pulses (P_{90-τ}-P_{180-τ}, with τ being a
 458 multiple of the MAS frequency), a rephasing of the signal is obtained, and broad features are
 459 not anymore distorted (Hahn, 1950; Vieira et al., 2016; Lucherelli et al., 2019). Cross
 460 polarization Magic Angle Spinning (CP/MAS) analysis is based on the magnetization transfer

461 from hydrogen to carbon atoms. It provides spectra with an improved signal-to-noise ratio, but
462 the quantification is not straightforward (Baccile et al., 2014; dela Rosa et al., 1992). Thus, the
463 intensity of the signal arising from a carbon atom depends on its hydrogen environment, and the
464 signal depends on the contact time. It requires an estimate of the fraction of undetected carbon
465 atoms through calculations constrained by the elemental composition of the sample. The
466 CP/MAS estimation is then much less direct than DP/MAS, and may suffer from error
467 propagation on speciation quantitation and elemental composition, as well as a non-
468 comprehensive identification of all involved carbon speciation.

469 Cody and Alexander, (2005) and Gardinier et al. (2000) both report CP/MAS NMR data
470 that provide quantitative estimates of the composition of IOM from Orgueil and Murchison. In
471 the case of the Murchison chondrite, the ratio of aliphatic to aromatic carbon atoms $F_{\text{ali}}/F_{\text{aro}}$
472 estimated by Gardinier et al. (2000) is slightly higher than that of Cody and Alexander (2005)
473 but it lies within the error bars (Fig. 8). In the case of Orgueil, the $F_{\text{ali}}/F_{\text{aro}}$ ratio from is lower
474 than that of Cody and Alexander (2005), but the error bars also overlap (Fig. 8). In contrast,
475 there is some significant disagreement regarding carbon atoms in oxygenated functions, in
476 particular for Orgueil (Fig. 8). These differences may be due to different experimental
477 procedures. Gardinier et al. (2000) investigated the spectral dependence upon contact time,
478 applied a correction accounting for undetected carbon atoms based on the bulk H/C ratio,
479 determined from the combustion experiment. The abundance of undetected aromatic carbon was
480 found significant, ranging from 20 – 29%. We note that the H/C value (0.7 in their study is
481 higher than that measured by Alexander et al. (2007, 2013) (0.588 ± 0.016 and 0.618 ,
482 respectively), which may have an impact on the derived abundances. Cody and Alexander
483 (2005) did not run systematic measurements as a function of contact time, but this latter was set
484 to 4.5 ms to fit with SP/MAS spectra. This quantitative interpretation of CP/MAS spectra
485 without investigations at variable contact time is not usual, and estimates might suffer from
486 biases (S. Derenne, personal communication; see also). In fact, in the details, the estimates
487 derived by Cody and Alexander (2005) from SP/MAS and CP/MAS show significant
488 differences. Due to these complex issues with CP/MAS, we have restricted to the SP/MAS data
489 from Cody and Alexander (2005) for comparison with our FTIR data.

490 We observe that $n_{\text{CH}_x}/n_{\text{C}=\text{C}}$ estimated from infrared data following equation 2 fits well
491 NMR data in the case of Orgueil, Murchison and Tagish Lake. $n_{\text{CH}_x}/n_{\text{C}=\text{C}}$ in EET 92042 is
492 underestimated by a factor of ~ 1.3 , though the error bars overlap (Fig. 8). The first explanation
493 of this moderate discrepancy is the chemical control of the A_{Aro} absorption cross-section by
494 oxygenated groups (Painter et al., 1981). The O/C ratio in EET 92042 ($\text{O/C}=16.6 \pm 0.2$) is lower
495 than those of Murchison (18.3 ± 0.3) and Orgueil (18.1 ± 0.2). These values are quite similar.
496 According to NMR data, the main oxygen speciation in chondritic IOM is carbonyl (ketone,
497 ester) and ether bridges. The estimations from SP/MAS NMR spectra are challenging due to the
498 faintness of the features and the poor signal-to-noise ratio, and they do not point to significant
499 variations between EET 92042, and Orgueil and Murchison. Altogether, there is no evidence of
500 a chemical control of the A_{Aro} absorption cross-section. A second tentative explanation is that
501 the SP/MAS data are not quantitative enough, due to the biases abovementioned. The only way
502 to firmly solve this issue would be to collect DP/MAS NMR spectra (MAS synchronized spin
503 echoes) of IOMs from those three chondrites.

504 Regarding carbonylated species, we observe that $n_{\text{CH}_x}/n_{\text{C=O}}$ is systematically higher than
505 NMR estimates, though the hierarchy Orgueil > Murchison > Tagish Lake is similar to NMR
506 estimates (Fig. 8). The number of bonds is equal to the number of carbon atoms in the case of
507 CH_x groups and carbonyl; therefore, the difference may be due here to different absorption
508 cross-sections of the C=O group between these IOMs and the HCO-tholin standard. As for the
509 C=C bonds, the local molecular environment plays a role in the control of the absorption cross-
510 section of the C=O stretching mode. Such variations have been observed for small molecules in
511 the solid-state, for instance, amorphous ices of formic acid and acetaldehyde, whose carbonyl
512 absorption cross-sections differ by a factor of 2 (Bouilloud et al., 2015; Hudson & Ferrante,
513 2020). Nevertheless, as mentioned in the previous section, the re-analysis of these IOM samples
514 by DP/MAS NMR (MAS synchronized spin echoes) is required to get a firm conclusion.

515 *To sum up, the H^{13}CO -tholins standard provides a suitable calibration for estimating*
516 *$n_{\text{CH}_x}/n_{\text{C=C}}$ in IOMs derived from FTIR measurement compared with SP/MAS NMR. In contrast,*
517 *$n_{\text{CH}_x}/n_{\text{C=O}}$ is overestimated in all classes of chondrites compared with the SP/MAS NMR from*
518 *Cody and Alexander (2005).*

519

520 **4.3 Composition of ligno-cellulosic coals**

521 We report now the composition of a series of coals of varying ranks from lignite to semi-
522 anthracite (Table S-2, Fig. S-5). The majority of coals plot within the Type III kerogen band on
523 the “Van Krevelen” diagram (Fig. 9a). Due to spectral congestion, the fit in the region 1800-
524 1500 cm^{-1} region is more complicated than for IOMs. We used four spectral components due to
525 ketones /quinone, aromatic branched with phenolic -OH (or -O-), and aromatic with a carboxylic
526 group (Chen et al., 2012; Painter et al., 1981; Petersen et al., 2008) (Fig. S-6). The abundance
527 of aromatic groups is then estimated through the two last components, and the C=O by the first
528 two components. Our results of the evolution trends are consistent with previous estimations
529 based on integrated abundance derived from IR spectra (Chen et al., 2012). No NMR data are
530 available for our coals, but NMR data are available for Chinese series of coals (Wei & Tang,
531 2018) and for the so-called Argonne Premium coals, a subset of the Penn State Coals Data bank
532 (de la Rosa et al., 1992). Figure 9b-c reports the FTIR and NMR CP/MAS estimates of Wei and
533 Tang (2018) plotted against the vitrinite reflectance. We observe two opposite trends: while the
534 NMR estimates point to a progressive decrease of $n_{\text{CH}_x}/n_{\text{C=C}}$, the FTIR estimates show an
535 increase up to the vitrinite reflectance of 1.73% and then a decline for the semi-anthracite
536 samples. In contrast, $n_{\text{CO}}/n_{\text{CH}_x}$ is consistent with NMR. This situation is opposite to what he had
537 with IOMs (Fig. 8).

538 The NMR estimates of Wei and Tang (2018) are, at least qualitatively, in agreement with
539 the progressive aromatization of the coals during diagenesis and catagenesis (Chen et al., 2012).
540 This supports the view that the ratio of the cross-section $A_{\text{CH}_x}/A_{\text{Aro}}$ varies with the vitrinite
541 reflectance, as previously reported (Painter et al., 1981; Dela Rosa et al., 1992). It also shows
542 that any semi-quantitative analysis based on IR measurements leads to inaccurate estimates of
543 the chemical evolution. NMR data collected by Wei & Tang (2018) were obtained in CP/MAS
544 with a 3 ms contact time. The publication does not report measurements over variable time

545 contact, nor the acquisition of single pulse spectra. In contrast, [Dela Rosa et al. \(1992\)](#) report
546 varying contact time CP/MAS measurements on Argonne Premium coals and one single pulse
547 (Bloch decay) analysis of Pittsburgh n°8 that fits the corresponding CP/MAS estimate. Muntean
548 et al. (1990) also report consistent CP/MAS and single pulse estimates in the case of Pocahontas
549 N°3, provided that the delay time remains < 75 μs. However, the agreement between both types
550 of measurements may be worse in the case of O-rich low-rank coals ([Dela Rosa et al., 1992](#)).
551 We have recalculated the aromaticity of the coals from [Wei and Tang \(2018\)](#) following the
552 definition of [Dela Rosa et al. \(1992\)](#), and found that the difference between estimates of the two
553 sets of data does not exceed 5%.

554 Finally, using those data and keeping in mind that uncertainties might be worse for the
555 more immature coals, we have calculated the cross-section ratio $A_{CHx}/A_{C=C}$ upon the vitrinite
556 reflectance (Fig. 9d). This curve is best fitted with a 6th order polynomial (Equation 3):

$$\frac{A_{CHx}}{A_{C=C}} = \sum_{i=0}^6 K_i (x - x_0)^i \quad (\text{Equation 3})$$

557
558 with $K_0=0.64599$; $K_1=0.23482$; $K_2=6.3733$; $K_3=-16.939$; $K_4=23.446$; $K_5=-14.846$;
559 $K_6=3.7045$ and $X_0=0.3$. This formula applies in the range $R_o = 0.3 - 2\%$, provided that a similar
560 fit model is used to decompose the coal infrared spectra. We observe that $A_{CHx}/A_{C=C}$ increases
561 and $A_{C=C}$ decreases, upon increasing the vitrinite reflectance R_o , consistently with control of the
562 absorption cross-section by oxygenated groups. The increase is quite high, around one order of
563 magnitude, which means that semi-quantitative sets of infrared data must be imperatively
564 corrected. However, further investigations combining DP/MAS NMR and FTIR measurements
565 on the same series of coals should provide more accurate data.

566

567 **5 CONCLUSION**

568 We have tested a protocol for quantifying the abundance of the CH_x, C=O and C=C
569 groups in chondritic IOMs and coals, based on a ¹³C model material characterized by DP/MAS
570 NMR and FTIR. The ratios of the cross-sections of these groups have been determined, and the
571 method has been applied to IOM samples extracted from CI, CM and CR chondrites, and to a
572 series of coals. The estimate of $n_{CHx}/n_{C=C}$ in IOM from CI and CM chondrites is fair, but
573 $n_{CHx}/n_{C=O}$ is overestimated. The estimate of $n_{CHx}/n_{C=C}$ in the CR chondrite is lower than the
574 estimation by SP/MAS published earlier. These discrepancies are due to the control of the
575 absorption of the C=O and C=C bonds by the local oxygenated chemical structure. In this regard,
576 the oxygen speciation in CR chondrites may be significantly different than that of CI and CM
577 chondrites. However, new NMR analyses of IOM from CR chondrites are necessary to test the
578 reproducibility of existing data. Regarding coals, the use of published NMR analyses shows that
579 the ratio $A_{CHx}/A_{C=C}$ varies with the vitrinite reflectance over an order of magnitude. Here as
580 well, the local oxygen speciation plays a critical control on A_{Aro} , which decreases with
581 increasing the vitrinite reflectance. We propose an analytical law for A_{CHx}/A_{Aro} , which should
582 be helpful to determine the aromaticity of any coal sample, provided its vitrinite reflectance is
583 known.

585 ACKNOWLEDGEMENTS

586 The authors are grateful to the financial support of the H2020 European Research Council (ERC)
587 (SOLARYS ERC-CoG2017_771691). We acknowledge Dr. Julien Alleon for the assistance
588 during STXM-XANES measurements at the HERMES beamline at the SOLEIL Synchrotron.
589 We also acknowledge Anne-Marie Blanchenet who prepared the microtomed section for STXM
590 analysis at the microscopy platform of the Lille University. We are thankful to the Raman
591 facility in ENS-Lyon, supported by the Institut National des Sciences de l'Univers (INSU). We
592 also thank Paul Craddock and an anonymous reviewer for helpful comments that improved the
593 manuscript.

594

595 Supplementary data

596 Supplementary data related to this article can be found at the Supporting Information part.

597

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779

780 Table 1. Chemical shifts, corrected relative abundances of the different functional carbon
781 groups in the initial and heated H¹³CO-tholins derived from Figure 1b-c.

782 Table 2. The functional carbon groups concentrations given by the XANES-based
783 quantification (Le Guillou et al., 2018).

784 Table 3. Integrated cross-section ratio calculation of the 400 °C H¹³CO-tholins based on the
785 quantitative NMR and the infrared spectral decomposition.

786

787 Figure 1. (a) The unheated and heated at 400 °C H¹³CO-Tholins recorded with a sample
788 spinning rate of 60 kHz and interscan delay of 30 seconds in the comparison with the IOM
789 Murchison and Orgueil (Cody et al., 2005, 2002, Gardinier et al., 2000). Deconvolution of the
790 solid state ¹³C DP/MAS NMR spectra of (b) the initial H¹³CO-tholins (c) and the 400 °C H¹³CO-
791 tholins

792 Figure 2. Raman spectrum of the 400°C H¹³CO- tholin. The G and D bands at ~1537 cm⁻¹ and
793 ~ 1310 cm⁻¹, respectively reveal a polyaromatic structure typical of coals and kerogens. The
794 low signal-to-noise ratio and spectral artifacts at the edge are due to the high fluorescence
795 background only partly corrected by the baseline correction.

796 Figure 3. (a) Normalized XANES spectra of the 400 °C H¹³CO and H¹²CO-tholins dominated
797 by aliphatic (-CH_x), C=C and C=O functional groups and (b) XANES and NMR methods
798 correlation of the 400 °C H¹³CO-tholins with the re-produced data from Le Guillou et al. (2018)
799 and Le Brech et al. (2016).

800 Figure 4. Corrected infrared spectra of H¹²CO and H¹³CO-tholins samples. Highlighted
801 attributions (CH₃ and CH₂ anti-symmetric modes and C=O and C=C stretching modes) are
802 those used for quantitative study.

803 Figure 5. Detailed components of CH_x mode in different phases (liquid, crystalline, amorphous)
804 in an example of alkane C₂₀H₄₂ (modified from MacPhail et al., 1984).

805 Figure 6. (a) Fit of the alkyl band of an IOM extracted from the Orgueil chondrite, obtained
806 through the artificial bees' algorithm. This fit was achieved with the 7 Gaussian model and all
807 components FWHM forced to 35 cm⁻¹. (b)-(c) Illusion of uncertainty of spectral decomposition
808 methods in different scenarios: Gaussian fix a FWHM of 35 cm⁻¹ (Blue); Voigt fix a FWHM of
809 20 – 40 cm⁻¹ (Yellow); Gaussian free a FWHM range of 20 - 40 cm⁻¹ (Green), Voigt free a
810 FWHM range of 20 - 40 cm⁻¹ (Red).

811 Figure 7. Normalized spectral intensity of the organic functional groups derived from the
812 calibration of C=O and C=C and CH_x groups using the DP/MAS NMR and FTIR calibration
813 for the 400 °C H¹³CO- tholins on (a) Murchison (CM2), (b) Orgueil (CI1), (c) EET 92042 (CR2)
814 and (d) Tagish Lake (C2-ung) IOM in the comparison with the SP/MAS ¹³C NMR spectra
815 (Cody et al., 2005) and CP/MAS ¹³C NMR (Gardinier et al., 2000).

816 Figure 8. Comparisons plots between (a) n_{CH_x}/n_{C=C} and n_{CH_x}/n_{C=O} ratios (b) n_{CH_x}/n_{C=C} and
817 n_{C=O}/n_{C=C} of IOM functional C groups (Murchison (CM2), Orgueil (CI1), EET92042 (CR2)
818 and Tagish Lake (C2-ung)) derived from FTIR-NMR quantification and the previous NMR's
819 measurement (Cody & Alexander, 2005; Gardinier et al., 2000; Yabuta et al., 2005).

820 Figure 9. Comparisons plots between (a) H/C and O/C atomic ratios of studied coals (b)
821 Normalized intensity of C=O, n_{C=O} + COOH(R) vs. vitrinite reflectance, (c) n_{CH_x}/n_{C=C} vs. vitrinite
822 reflectance and (d) Calculated A_{CH_x}/A_{C=C} vs. vitrinite reflectance derived from FTIR-NMR
823 quantification and the previous NMR's measurement (Wei & Tang, 2018).