



HAL
open science

Hydrogen abundance estimation and distribution on (101955) Bennu

A. Praet, M. A. Barucci, B. E. Clark, H. H. Kaplan, A. A. Simon, V. E. Hamilton, J. P. Emery, E. S. Howell, L. F. Lim, X. -D. Zou, et al.

► **To cite this version:**

A. Praet, M. A. Barucci, B. E. Clark, H. H. Kaplan, A. A. Simon, et al. Hydrogen abundance estimation and distribution on (101955) Bennu. *Icarus*, 2021, 363, pp.4123-4142. 10.1016/j.icarus.2021.114427. hal-03502255

HAL Id: hal-03502255

<https://hal.science/hal-03502255v1>

Submitted on 24 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 Hydrogen Abundance Estimation and Distribution on (101955) Bennu

2
3 Authors: A. Praet*¹, M. A. Barucci¹, B. E. Clark², H. H. Kaplan³, A. A. Simon³, V. E. Hamilton⁴, J.
4 P. Emery^{5,6}, E. S. Howell⁷, L. F. Lim³, X.-D. Zou⁸, J.-Y. Li⁸, D. C. Reuter³, F. Merlin¹, J. D. P.
5 Deshapriya¹, S. Fornasier^{1,9}, P. H. Hasselmann¹, G. Poggiali^{10,11}, S. Ferrone², J. R. Brucato¹⁰, D.
6 Takir¹², E. Cloutis¹³, H. C. Connolly Jr^{7,14}, M. Fulchignoni¹, D. S. Lauretta⁷.

7
8 ¹LESIA, Observatoire de Paris, Université PSL, CNRS, Université de Paris, Sorbonne Université,
9 5 place Jules Janssen, 92195 Meudon, France,

10 ²Department of Physics, Ithaca College, Ithaca, NY, USA,

11 ³NASA Goddard Space Flight Center, Greenbelt, MD, USA,

12 ⁴Southwest Research Institute, Boulder, CO, USA,

13 ⁵University of Tennessee, Knoxville, TN, USA,

14 ⁶Northern Arizona University, Flagstaff, AZ, USA,

15 ⁷Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA,

16 ⁸Planetary Science Institute, Tucson, AZ, USA,

17 ⁹Institut Universitaire de France (IUF), Paris, France,

18 ¹⁰INAF–Arcetri Astrophysical Observatory, Florence, Italy,

19 ¹¹Department of Physics and Astronomy, University of Florence, Florence, Italy,

20 ¹²JETS/ARES, NASA JSC, Houston, TX, USA,

21 ¹³University of Winnipeg, Winnipeg, Manitoba, Canada R3B 2E9,

22 ¹⁴Department of Geology, Rowan University, Glassboro, NJ, USA.

23

24 **Abstract:**

25 Asteroids were likely a major source of volatiles and water to early Earth. Quantifying the
26 hydration of asteroids is necessary to constrain models of the formation and evolution of the
27 Solar System and the origin of Life on Earth. The OSIRIS-REx (Origins, Spectral Interpretation,
28 Resource Identification, and Security–Regolith Explorer) mission showed that near-Earth
29 asteroid (101955) Bennu contains widespread, abundant hydrated phyllosilicates, **indicated**
30 **by a ubiquitous absorption at ~2.7 μm. The objective of this work is to quantify the**
31 **hydration—that is, the hydrogen content—of phyllosilicates on Bennu’s surface and**
32 **investigate how this hydration varies spatially. We** analyse spectral parameters
33 **(normalized optical path length, NOPL; effective single-scattering albedo, ESPAT; and**
34 **Gaussian modeling) computed from the hydrated phyllosilicate absorption band of spatially**
35 **resolved visible–near-infrared spectra acquired by OVIRS (the OSIRIS-REx Visible and**
36 **InfraRed Spectrometer). We also computed the same spectral parameters using laboratory-**
37 **measured spectra of meteorites including CMs, CIs, and the ungrouped C2 Tagish Lake. We**
38 **estimate the mean hydrogen content of water and hydroxyl groups in hydrated**
39 **phyllosilicates on Bennu’s surface to be 0.71 ± 0.16 wt.%. This value is consistent with the**
40 **hydration range of some aqueously altered meteorites (CMs, C2 Tagish Lake), but not the**
41 **most aqueously altered group (CIs). The sample collection site of the OSIRIS-REx mission has**
42 **slightly higher hydrogen content than average. Spatial variations in hydrogen content on**
43 **Bennu’s surface are linked to geomorphology, and may have been partially inherited from its**
44 **parent body.**

45

46 **Keywords:** Asteroid Bennu; Asteroid Surfaces; Asteroid Composition; Meteorites;
47 Spectroscopy.

48 * Corresponding author. alice.praet@obspm.fr (A. Praet).

49 **1. Introduction**

50 The OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) (Reuter et al., 2018) collected
51 visible–near-infrared (VNIR) spectra in the range of 0.4 to 4.3 μm during the spacecraft’s
52 approach to and global mapping of Bennu (Lauretta et al., 2017). Early observations showed
53 that Bennu’s strongest spectral feature is the absorption band **in the 3- μm region** (at $2.74 \pm$
54 $0.01 \mu\text{m}$ **for Bennu**) associated with the presence of OH^- or H_2O bound in hydrated
55 phyllosilicates (Hamilton et al., 2019). The band position and ubiquity of **this feature on**
56 **Bennu** indicates the global presence of Mg-phyllosilicate minerals that are the result of an
57 advanced stage of hydrothermal alteration (Hamilton et al., 2019).

58 **In addition, Simon et al. (2020b) found minor absorption bands (characterized by a depth**
59 **less than 5%) centered near 1.4, 1.8, and 2.3 μm , among others. The 1.4- μm absorption**
60 **band is due to the first overtone of the OH stretch band (Clark et al., 1999), and the band**
61 **near 1.8 could be associated with the combination the H_2O bending and the OH stretch**
62 **that occurs near 1.9 μm (Clark et al., 1999). As for the minor absorption band detected**
63 **near 2.3 μm , it is insufficiently clear whether it is due to phyllosilicates (cation–OH bound),**
64 **carbonates, or other species (Simon et al., 2020b).**

65 Bennu is a rubble-pile asteroid, **believed to be part of the Eulalia/New Polana families** that
66 reaccumulated from the fragments of a $\sim 100\text{-km}$ -diameter parent asteroid that was broken
67 apart by impacts (Bottke et al., 2015; DellaGiustina and Emery et al., 2019; Jutzi and Michel,
68 2020; Michel and Ballouz et al., 2020; Walsh et al., 2013). **Through simulations, Michel and**
69 **Ballouz et al. (2020) predicted that Bennu could originate from the catastrophic disruption**
70 **of an already hydrated parent body sourced from a localized region, and that similarly**
71 **heated unbound material during collision could result into a homogenous asteroid surface.**
72 **This is consistent with Amsellem (2020) who, using radiometric dating of five heated CM**
73 **carbonaceous chondrites, found that the CM heating event (at least 3 Ga after the Solar**
74 **System formation) could have correlated with the parent-body disruption (i.e., the**
75 **asteroid family-forming event) of New Polana and Eulalia families, for example, with age**
76 **estimations of 1.4 ± 0.15 Ga and 0.8 ± 0.1 Ga, respectively (Walsh et al., 2013; Bottke et al.,**
77 **2015).**

78 Image data acquired by OSIRIS-REx showed that Bennu has a rough and rocky surface
79 covered with boulders up to ~ 100 m in longest dimension (Daly et al., 2020; DellaGiustina &
80 Emery et al., 2019; Jawin et al., 2020; Walsh et al. 2019). There are two distinct populations
81 of boulders distinguishable by their albedo, texture and thermal inertia (DellaGiustina et al.,
82 2020). The low-reflectance population ($\leq 4.9\%$ normal albedo) has a rough, hummocky
83 texture and encompasses a range of sizes. The high-reflectance population ($> 4.9\%$ normal
84 albedo) has smoother and more angular features and includes only boulders $< \sim 20$ m. In the
85 global map of the 2.7- μm hydration band depth (spectrum spot spatial resolution of ~ 20 m x
86 30 m per spectrum, map spatial resolution of ~ 600 m²), the shallowest band depths are
87 associated with the darkest boulders, which are also the hottest, as well as with the
88 equatorial band (-20° to 20° latitude) (Simon et al., 2020a, see also **Figure 4**), which may be
89 due to the differences in the mineralogy resulting from aqueous alteration (Kaplan et al.,
90 2020).

91
92 The closest spectral analogs to Bennu (Clark et al., 2011) and other **low albedo** asteroids
93 (e.g. Clark et al., 2010; Fornasier et al., 1999) are carbonaceous chondrite (CC) meteorites,

94 which have a continuum of mineralogical, petrological, and textural properties resulting
95 from mild to strong aqueous alteration on their parent bodies. These properties can be used
96 to constrain scenarios of geological evolution of small planetary bodies within the early solar
97 system material (McSween et al., 2018). VNIR reflectance spectra of these meteorites
98 measured in the laboratory have been analyzed to understand the spectral properties of
99 hydrated minerals associated with varying degrees of alteration (Garenne et al. 2016; Potin
100 et al. 2020; Takir and Emery, 2015). The first spectral behaviour analysis of the data from the
101 OSIRIS-REx spacecraft, even if different from all available meteorites, showed that Bennu is
102 most consistent with CM or CI chondrites (Hamilton et al., 2019), which are the most
103 aqueously altered of the CC meteorites.

104
105 Previous studies of CM and CI chondrite hydration indicate that these meteorites have a
106 range of hydration (defined as hydrogen wt.% in H₂O and OH⁻) that is correlated with the
107 degree of alteration (**Robert and Epstein, 1982**; Alexander et al., 2007, 2012, 2013). These
108 bulk-composition studies made assumptions about where hydrogen is hosted—for example,
109 in minerals as opposed to organics—because direct detections of H₂O and OH⁻ *in situ* were
110 not possible. However, subsequent studies found that most hydrated species are hosted in
111 phyllosilicates, in particular Mg- and Fe-serpentine and saponite (Takir et al., 2013). Howard
112 et al. (2015) showed that the majority of hydrogen is contained in phyllosilicates for the CM,
113 ungrouped type 2, and CR chondrites. Phyllosilicate composition changes from Fe-rich to
114 Mg-rich with increasing alteration (**McSween, 1979**).

115
116 Laboratory studies of C chondrites have shown how hydration may be quantified from VNIR
117 spectra (**Pommerol and Schmitt, 2008a, 2008b and references therein**). Milliken and
118 Mustard (2007) developed an approach where the effective single-particle absorption
119 thickness (ESPAT) and the normalized optical path length (NOPL) of a spectrum can be linked
120 directly to water content (see also Milliken and Mustard, 2005; Garenne et al., 2016). This
121 approach has since been applied to global spectral datasets from Mars (e.g. Mustard et al.,
122 2008) and the Moon (e.g. Li and Milliken, 2017). A similar study using H wt.% and spectra of
123 C chondrites found that ESPAT and band depth can be used to estimate hydration for these
124 meteorites (Garenne et al, 2016). Other analyses of C chondrites showed that Gaussian
125 modeling of the 2.7- μ m absorption feature could be directly related to H wt.% of the
126 samples (Kaplan et al., 2019; Potin et al., 2020).

127
128 Correlation between meteorite spectral parameters and their hydration, defined as H
129 content of the water and hydroxyl groups (H₂O and OH⁻) in the hydrated phyllosilicates
130 (hereafter, H content) allowed us to estimate Bennu's surface H content, using Bennu
131 spectral parameters. We discuss how Bennu H content estimation compares to the ones of
132 CC meteorites. We, then, explore in detail how the hydration of Bennu's surface spatially
133 varies. The implications of the H content estimation as well as its spatial variations are
134 fundamental for the understanding of the cosmochemical history and aqueous alteration of
135 Bennu's parent body, as well as for the sample of Bennu that the OSIRIS-REx spacecraft will
136 return to Earth in 2023 (Lauretta et al., 2017).

137
138
139
140

141 2. Data and Methods

142 2.1 Bennu data

143 In April 2019, OVIRS, onboard the OSIRIS-REx spacecraft, acquired visible-infrared spectra,
144 from 0.4 to 4.3 μm , of asteroid (101955) Bennu from a range of 5km. Global coverage was
145 obtained at a solar phase angle of 8-10 degrees, with approximately 30% overlap from one
146 spectrometer spot to the next (Simon et al., 2020a). **The Bennu spectral data we used were**
147 **acquired during the third Equatorial Station (EQ3) of the Detailed Survey phase, on May 9**
148 **2019, at 12:30 pm local solar time (Lauretta et al., 2017). This data set allows both careful**
149 **spectral analysis at a spectral resolution of 2 nm from 0.4 to 2.4 μm and 5 nm from 2.4 to**
150 **4.3 μm , and global mapping at a spatial resolution of 20x30 meters per spectrum.**

151 Spectra acquired were then calibrated and resampled. Finally, the thermal tail of each
152 spectrum is removed and all spectra are divided by solar flux (Simon et al., 2020a) and then
153 photometrically corrected (Zou et al., 2021). The spectra were filtered according to their
154 viewing geometry with incidence and emergence angles both inferior to 70° , to eliminate
155 viewing geometry artefacts. Spectra were also filtered for spikes and saturation. Our data set
156 after filtering is 7089 spectra for EQ3 station.

157 The OVIRS spectral reflectance of Bennu's surface depends on the light scattering geometry.
158 In order to make comparisons between different areas and quantitatively interpret the
159 spectra based on laboratory measurements, the observations need to be photometrically
160 corrected to the same geometry. We choose a common geometry often used in laboratory
161 settings, where Reflectance Factor (REFF) is measured at $(i_0, e_0, \alpha_0) = (0^\circ, 30^\circ, 30^\circ)$. OVIRS
162 data are obtained in units of Radiance Factor (RADF). A McEwen model is used to correct
163 the measured RADF values of each spectral wavelength to the reference geometry. Then,
164 RADF data are converted to units of REFF for comparison with laboratory measurements.
165 The details of the photometric correction are explained in (Zou et al., 2021).

166
167 The OVIRS spectra are calibrated on a spot-by-spot basis using an automated pipeline that
168 subtracts a nearby deep space background level, subtracts out-of-band signal (IR leakage in
169 all filters $< 2.95 \mu\text{m}$), converts to absolute physical radiance units and screens for outlier
170 pixels (Simon et al., 2018). Each spectrum is then resampled onto a common wavelength axis
171 with 2-nm sampling below 2.4 μm and 5-nm sampling above 2.4 μm . As part of the signal
172 above 2.2 μm is from thermal radiance, a thermal tail is calculated and removed from each
173 spectrum before dividing by a range-corrected solar spectrum to convert to reflectance
174 (Simon et al., 2020a). There are two sources of uncertainty in the final spectra: channel-to-
175 channel noise, which is calculated based on read noise and photon noise, and absolute
176 radiance calibration. The absolute radiometric uncertainty affects the overall radiance across
177 the full spectrum with no particular wavelength dependence. However, two terms do have
178 a spectral dependence that may affect the hydration band. First, the out-of-band signal is
179 calculated by summing the long wavelength radiance and multiplying by coefficients for
180 each wavelength derived from perfect blackbody source data. Any spot that covers a mixed
181 temperature scene may potentially have an error in this correction that increases with
182 decreasing wavelength in each filter segment (i.e., it is larger at 1.7 μm than at 2.9 μm). The
183 second uncertainty comes from the thermal tail correction that may remove too much, or
184 not enough, radiance, if the thermal tail fit is **not well determined**. Both of these contribute
185 a few percent of uncertainty to the absolute radiance. The uncertainty plotted in Figure 1a
186 represents the standard error of the mean normalized spectrum.

187

188 **2.2 Meteorite data**

189 The meteorite dataset that we assembled for this study is composed of 39 hydrated CC
190 meteorites (**Appendix A**) for which bulk hydrogen values have been independently
191 measured (Alexander et al., 2012, 2013; Garenne et al., 2016).

192 All the selected meteorites used in this work, were powdered and spectra were measured
193 under asteroid-like conditions (vacuum- and thermally-desiccated conditions) (**Appendix A**).
194 Meteorite chips from Takir et al. (2013, 2019) were grounded into ~100- μm powder and no
195 grain size distributions were measured due to the small amount of meteorite sample. The
196 meteorites from Potin et al. (2020) and Garenne et al. (2016) were powdered manually but
197 not sieved to keep a large grain size distribution.

198 An additional spectrum was collected for Mighei (with grain size < 500 μm) at INAF-
199 Astrophysical Observatory of Arcetri in Firenze, Italy (*Poggiali personal communication*).
200 Milliken and Mustard (2007) studied the effect of increasing spectrum particle size class
201 (from <25 μm to 125–250 μm) on spectral parameters such as NOPL and ESPAT calculated
202 on the spectrum 2.7- μm hydration band. They showed that these spectral parameters
203 increase with increasing particle size for the same water content (H_2O wt.%) of the sample.
204 The meteorite spectra chosen in this study all present large grain size distribution with
205 different maximum grain size. This difference is not believed to impact spectral
206 measurements, as small-sized material dominates the spectral signature of planetary
207 surfaces or meteorite powders characterized by a large particle size distribution.
208

209 The meteorite H contents used in this study are calculated in Alexander et al. (2012, 2013).
210 The authors have measured the bulk carbon content as well as bulk hydrogen content.
211 Assuming all carbon is in the organic matter, they then deduced the organic hydrogen
212 content using the typical Insoluble Organic Matter (IOM) hydrogen to carbon ratio of CR
213 meteorites and CM meteorites. The organic hydrogen content is subtracted from the bulk
214 hydrogen content to derive the bulk hydrogen content in water and hydroxyl groups of
215 hydrated phyllosilicates, i.e.: **H content** which is reported in **Appendix A**. In the case of
216 meteorites for which the H contents were not calculated by Alexander et al. (2012, 2013),
217 we did the same calculations as explained above, using the meteorite bulk composition
218 measurements (bulk, H, bulk C and H/C values) from the literature. In the case of the Orgueil
219 and Tagish Lake meteorites, several samples were analyzed and several **different** hydrogen
220 content values were ultimately derived (Alexander et al., 2012; Gilmore et al., 2019), and our
221 results reflect the variability in the reported values.
222

223 **2.3 I/F spectrum conversion into single-scattering albedo (SSA) spectrum**

224 In order to calculate the effective single-particle absorption thickness (ESPAT) parameter, we
225 converted Bennu photometrically corrected I/F spectra into single-scattering albedo spectra
226 using the five-parameter form of a Hapke model (Li et al., 2007a, 2007b, 2009) that **includes**
227 a single-scattering albedo term (ω), a single-term Henyey-Greenstein (HG) function (p) with
228 an asymmetry factor (g), a roughness parameter (θ) and finally a shadow hiding opposition
229 effect term (SHOE) characterized by its width (h) and its height (B_0). The two latter
230 parameters are fixed to 0.11 and 2.06, respectively, as derived from the disk-integrated
231 phase function based on the OCAMS images obtained during the approach to the asteroid in
232 December 2018.

233 The Hapke model is then run on **the** global-surface spectral data set in order to obtained the
234 following global Hapke modeling parameters for the model best fit: ω , g , θ , geometric

235 albedo and bond albedo and goodness-of-fit indicators root-mean-square (RMS), relative
 236 root-mean-square (RRMS). The best fit **is** deduced from the smallest chi-square test (χ^2)
 237 value when searching in parameter space (**from** Li et al., in **revision**). The same Hapke
 238 Isotropic Multiple Scattering Approximation (IMSA) model (Hapke, 1993, 2002) was then re-
 239 run on global-surface I/F spectral data set (EQ3) using the previously obtained global Hapke
 240 modeling parameters (**i.e. the global average Hapke model parameters from Li et al., in**
 241 **revision**), with the porosity term calculated using Helfenstein and Shepard (2011), leaving
 242 SSA as a free parameter at every channel.

243
 244 In the case of meteorite spectra measured in **the** laboratory: we apply several simplifications
 245 **to** the Hapke model (Beck et al., 2010). The simplifications (Garenne et al., 2016; Milliken
 246 and Mustard, 2007) are the absence of opposition effects (no SHOE, no CBOE), therefore the
 247 backscattering term is negligible ($B(g) = 0$), and the phase function is **assumed to be** isotropic
 248 (the scattering term is set to $p(g) = 1$). These are reasonable **assumptions** for particulate
 249 samples in which particles are in **intimate** contact (powder) and larger in size than the
 250 wavelength (from 2.6 to 3.3 μm) (Milliken and Mustard, 2007).

251 252 **2.4 ESPAT parameter calculation**

253 The Effective Single Particle Absorption Thickness parameter ($W(\lambda)$, ESPAT) function is a
 254 quantity defined by Hapke (1993) related to the absorption coefficient, volume of particles
 255 and the single-scattering albedo (**Equation 1**).

256 Dealing with such quantities has proved to have some advantages: Hapke (1993) has shown
 257 that the ESPAT function is quasi-linear, proportional for a wide range of effective particle
 258 size determined by the value of internal scattered coefficient; subsequently, Milliken &
 259 Mustard (2005) found that this function is also linearly proportional for a wide range of
 260 absolute water content (0-15 %wt H_2O). ESPAT function is, therefore, most useful when the
 261 medium consists of particles that are sufficiently small (Hapke, 1993) or surface roughness
 262 equivalent to small particle size. It also indicates that the water content is quasi-linear in
 263 respect with the effective particle size.

264 When the extinction coefficient ($Q_E(\lambda)$) is assumed to be 1, then the scattering coefficient
 265 ($Q_S(\lambda)$) is equivalent to the volume-average single-scattering albedo ($\omega(\lambda)$). Thus, the ESPAT
 266 parameter can be calculated using volume-average single-scattering albedo (ω) (**Equation 1**),
 267 Milliken and Mustard (2007).

$$268 \quad W(\lambda) = \frac{1-\omega(\lambda)}{\omega(\lambda)} \quad (1)$$

269 **Equation 1** shows that when there is no absorption ($\omega(\lambda) = 1$), the ESPAT parameter is null
 270 ($W(\lambda) = 0$). However, for dark material: $\omega(\lambda)$ values are **less than 1** in **the** OVIRS wavelength
 271 range (0.4 to 4.3 μm), even when no absorption occurs. Therefore, following Milliken and
 272 Mustard (2007), we divide $\omega(\lambda)$ values by their continuum fits (using the maximum single
 273 scattering albedo value: $\omega_{\text{max}}(\lambda)$) to isolate the absorption band studied, with the following
 274 equation (**Equation 2**):

$$275 \quad W(\lambda) = \frac{1-\frac{\omega(\lambda)}{\omega_{\text{max}}(\lambda)}}{\frac{\omega(\lambda)}{\omega_{\text{max}}(\lambda)}} \quad (2)$$

276 **A** linear continuum is fitted using the reflectance average of three OVIRS wavelength
 277 channels as left and right anchor points (at 2.6 and 3.3 μm). The mean wavelength of the
 278 hydration band minimum position for the EQ3 data set corrected with McEwen model is

279 2.73 ± 0.01 μm; therefore, the ESPAT parameter was calculated at 2.73 μm, using also three-
280 wavelength channel average.

281

282 **2.5 NOPL parameter calculation**

283 The normalized optical path length (NOPL) is calculated on absolute reflectance spectra of
284 Bennu's surface and meteorites following the calculation of Milliken and Mustard (2007, see
285 also Garenne et al., 2016; Milliken and Mustard, 2005; Milliken et al. 2007). The NOPL
286 parameter at a defined wavelength (λ, here 2.73 μm) is calculated using the reflectance
287 (R(λ)) as well as the reflectance of the linear continuum (R_c(λ)) fitted between 2.6 μm and
288 3.3 μm (**Equation 3**). We computed three-wavelength channel average for each linear
289 continuum anchor point as well as for the centre point.

$$290 \quad NOPL(\lambda) = \frac{-\ln(R(\lambda)+1-R_c(\lambda))}{-\ln(1-R_c(\lambda))} \quad (3)$$

291

292 **2.6 Band gaussian modeling**

293

294 **2.6.1 3-μm Region Absorption Band**

295 **The absorption band in the 2.7-μm region is caused by the combination of vibration**
296 **fundamental mode and overtones of H₂O, OH, and cation–OH bonds.**

297 **H₂O and OH groups are present in the mineral structure of phyllosilicates or can be**
298 **adsorbed onto the surface of mineral grains in the case of H₂O. In the scope of this work,**
299 **we focus our analysis on the absorption contribution of OH and H₂O in the region between**
300 **2.6 and 3.3 μm.**

301 **The hydroxyl O–H bond has one stretching vibration fundamental mode, which depends**
302 **on the cation to which the OH is bonded (Bishop et al., 2002). It can occur between 2.67**
303 **(Farmer, 1974) and 3.45 μm (Ryskin, 1974), and more typically between 2.7 and 2.8 μm**
304 **(Clark et al., 1990). Absorptions near 2.72 and 2.75–2.76 μm are characteristic to**
305 **magnesium-rich (Mg-OH) and aluminium-rich (Al-OH) phyllosilicates, respectively**
306 **(DeSanctis et al., 2016). The OH stretch vibration of iron-rich (Fe-OH) phyllosilicates occurs**
307 **near 2.8 μm (Manceau et al., 2000). Water (H₂O) in minerals is characterised by three**
308 **vibration fundamental modes (ν). A symmetric OH stretch in the water molecule (ν₁)**
309 **occurs near 3.106 μm and the asymmetric OH stretch (ν₃) occurs near 2.903 μm, whereas**
310 **the H-O-H bend (ν₂) occurs near 6.079 μm (Clark et al., 1990). Adsorbed water was also**
311 **found to cause an absorption band near 2.85 μm.**

312

313 **2.6.2 Gaussian modeling**

314 **Gaussian modeling allows us to distinguish and define the different contributions of**
315 **radical-OH and H₂O stretching modes in the 2.7-μm region absorption band.**

316 The absorption band due to hydrated phyllosilicates in Bennu's spectra as well as in
317 meteorite spectra were modelled using several Gaussians. The 2.7-μm region absorption
318 band was modelled using Gaussians from 2.6 to 3.3 μm for Bennu's EQ3 average spectrum
319 and using continuum anchor points adapted for each meteorite, using up to five Gaussian
320 curve fits and a linear continuum.

321 Each Gaussian is diagnostic of one or several different stretching modes of OH⁻ and/or H₂O
322 groups, depending on their center wavelength (2.72, 2.75, 2.8, 2.9 and 3.1 μm).

323 While these five Gaussian curves combine to create the composite absorption feature from
324 ~2.6 to ~3.3 μm, each individual Gaussian curve is associated with energy required by a

325 slightly different hydrogen-rich functional group linked to hydroxyl (OH⁻) and water (H₂O)
326 (Clark et al., 1999; DeSanctis et al., 2017; Rivkin et al., 2015).

327
328 In our analysis, we use the area of the second Gaussian curve centered (on average) at 2.75
329 μm (hereafter the G2 area) that is associated with OH⁻ (Kaplan et al., 2019). Of the three
330 methods we have employed to assess H content of Bennu, Gaussian modeling of the
331 absorption band has the highest number of free parameters and, as a result, the greatest
332 uncertainty due to the large number of local model solutions, which leads to noisier results.
333 We therefore have decided not to include Gaussian modelling results in our final map of
334 Bennu mean H content, as we cannot distinguish spatial features within the noise. However,
335 the gaussian modeling of the hydrated phyllosilicates is an independent test to confirm the
336 global average H content values obtained from ESPAT and NOPL.

337 338 **2.7 Mapping**

339 In this study, we use the 200,000-facet Palmer shape model version 20 (Barnouin et al.,
340 2019). For each facet, a weighted average value of the spectral parameter of all overlapping
341 OVIRS spots is calculated using the percentage of overlap between OVIRS spot and the facet
342 as weight (Ferrone et al., 2021). As described before, each spectrum thermal tail is removed
343 and all spectra are photometrically corrected. Finally, all spectral parameter maps are
344 overlaid on the global basemap (Bennett et al., 2020).

345

346 **3. Results**

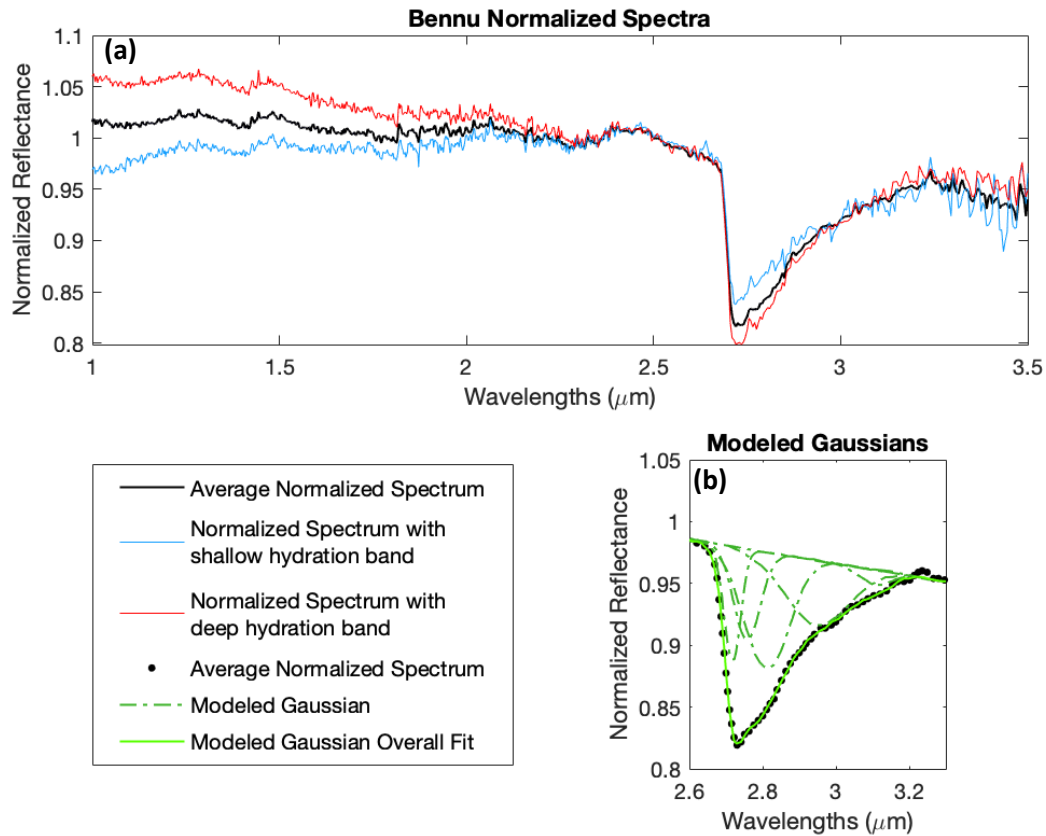
347 We calculated the NOPL and the ESPAT parameters and performed Gaussian modeling of the
348 2.7-μm absorption band for the absolute reflectance spectra of a set of 39 meteorites
349 (Appendix A). We find a linear correlation between our calculated spectral parameters and
350 the H content of the meteorites. Using this correlation, we estimated the H content of
351 Bennu's surface as well as its spatial variation, using the same spectral parameters
352 calculated from Bennu's reflectance spectra.

353

354 **3.1 Hydration Estimation**

355 The spatially resolved spectral dataset of Bennu's global surface includes 7089 spectra, with
356 incidence and emergence angles less than 70°, and covers Bennu's surface from -80°S and
357 +80°N latitude. The average EQ3 Bennu spectrum is shown in Figure 1a. Our Gaussian model
358 of Bennu's EQ3 average spectrum can be found in Figure 1b.

359



360

361 **Figure 1: a)** Average normalized (at $2.5\mu\text{m}$) EQ3 Benu spectrum with standard error of the
 362 mean ($\sim 5 \cdot 10^{-4}$), as well as the spectra showing the deepest and shallowest hydration band
 363 in red and blue respectively. **b)** Gaussian model result obtained for the average EQ3
 364 spectrum (normalized to 1.0 @ $2.5\mu\text{m}$), showing five separate Gaussian curves (dotted green
 365 lines), for which the composite spectrum (solid green curve), agrees well with the measured
 366 spectrum (blue dots).

367

368 We find a linear correlation between each of the spectral parameters (ESPA, NOPL and
 369 Gaussian), we calculated from the meteorite spectra and the H content of the meteorites
 370 (**Figure 2, a to c**). The Spearman rank correlation was computed for each linear regression:
 371 the rank correlation coefficient (R) and the two-sided significance of its deviation from 0 (p -
 372 value) (**Figure 2**). In all three cases, the correlation is strong (p -value < 0.01 and $|R| > 0.6$).

373

374

375

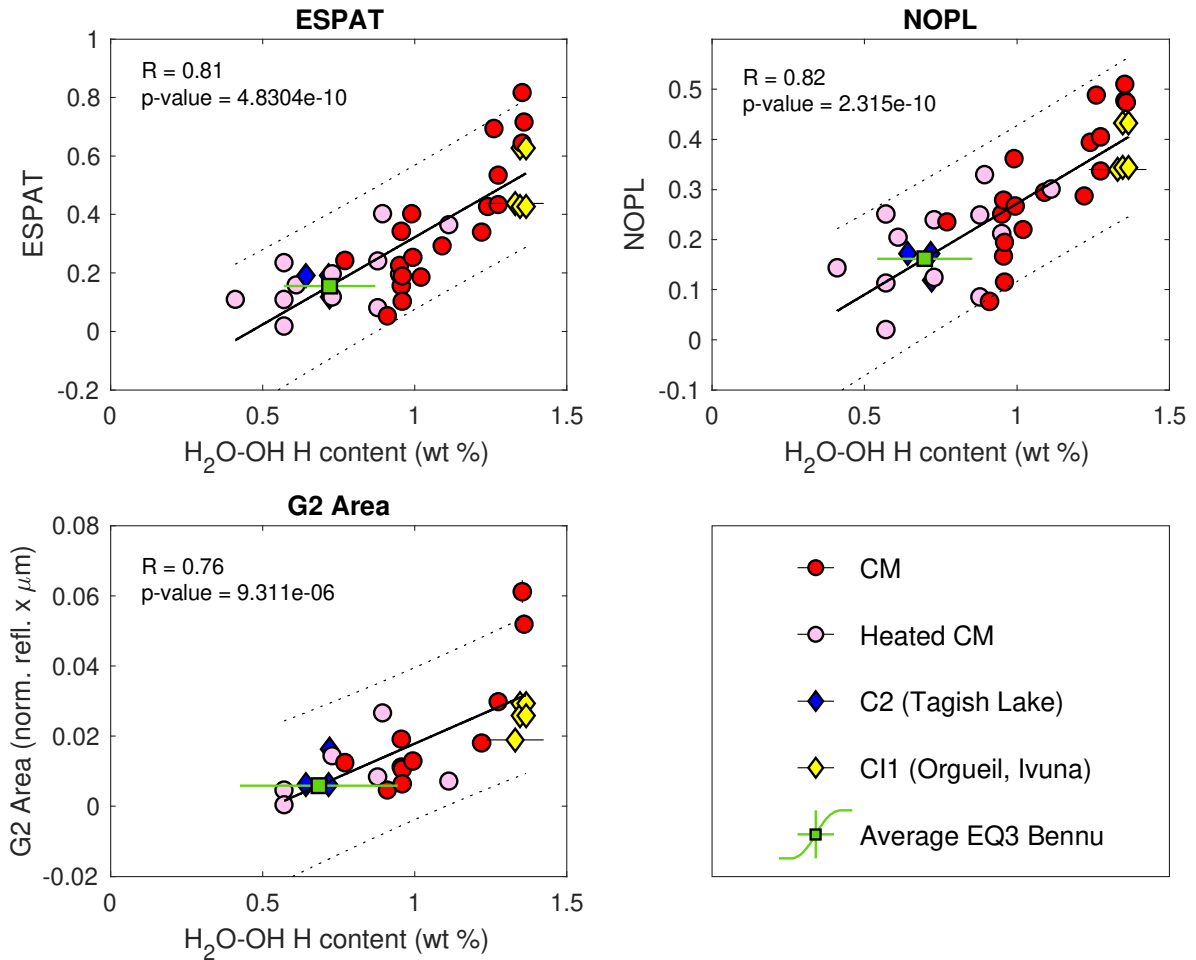
376

377

378

379

380



381
 382 **Figure 2:** Linear correlation between the H content of meteorites (**Appendix A**) and **a)** their
 383 ESPAT parameter, **b)** the NOPL parameter, and **c)** G2 area, for different types of hydrated CC
 384 meteorites and Bennu. The thick black line is the linear regression of the meteorite data ; the
 385 two dashed black lines define the prediction bounds, which indicate the area in which a new
 386 data point would fall with 95% probability. Spearman rank correlation coefficient (R) and p -
 387 value are reported. Parameter errors for the meteorites are smaller than the symbols. The
 388 values for Bennu (**Table 1**) were determined by using the meteorite correlations. The vertical
 389 error bars on Bennu mean ESPAT, NOPL and G2 area are **their averaged uncertainty (Table**
 390 **1) and are inside their symbol**. The H content horizontal bar is computed for each method
 391 by propagating the error in the determination of the linear regression coefficients (**which**
 392 **represents the uncertainty linked to the linear regression equation**) as well as the mean
 393 **uncertainty**.

394 We can therefore use the linear correlations between each spectral parameter and H
 395 content in the meteorites to estimate the H content of Bennu. **Figure 2** shows the average,
 396 maximum, and minimum values of each spectral parameter obtained from the EQ3 spectra
 397 of Bennu. The H content error is estimated using the propagation error associated **with** the
 398 linear correlation from the meteorites. We estimate the average H content of Bennu's
 399 surface to be 0.72 ± 0.15 wt.% using ESPAT, 0.70 ± 0.16 wt.% using NOPL, and 0.69 ± 0.26
 400 wt.% using the G2 area. All average H content values that we derived for Bennu's surface are
 401 summarized in **Table 1**. The three different spectral parameters indicate consistent H
 402 content within the error bars. However, the Gaussian modeling method for G2 area presents

403 a large number of free parameters, and the non-**uniqueness** of the **Gaussian models**
 404 enhance its noise levels; therefore, we do not use the H content range derived from G2 area
 405 to compute **or map** the **mean** H content value of Bennu’s surface. On the basis of the ESPAT
 406 and NOPL methods, Bennu’s surface mean H content is 0.71 ± 0.16 wt.%. This range of
 407 values is consistent with the C2 Tagish Lake and heated CM meteorites and not consistent
 408 with the most heavily aqueously altered meteorites, the CIs (higher H content 1.330-1.366
 409 wt.%, **Figure 2**). H content values obtained by measuring the NOPL parameter are consistent
 410 with values from ESPAT and G2 area fits to Bennu’s 2.7- μm absorption band, which adds
 411 confidence to the result.

412

413 **Table 1:** Estimation of the **global average H content (phyllosilicate H₂O and OH group**
 414 **hydrogen content)** of Bennu's surface derived from ESPAT, NOPL, and G2 area, **with the**
 415 **error derived from the uncertainties of each set of linear correlation coefficients.** The
 416 average H content computed with NOPL and ESPAT **methods** is also reported. **The mean**
 417 **value of each parameter as well as their associated mean uncertainty is reported in the**
 418 **first column.**

Parameter (Mean value \pm uncertainty unit)	Estimated Bennu global average H content (wt.%)
ESPAT (0.155 ± 0.010)	0.72 ± 0.15
NOPL (0.162 ± 0.010)	0.70 ± 0.16
G2 Area (0.006 ± 0.0007 normalized REFF. μm)	0.69 ± 0.26
NOPL & ESPAT avg	0.71 ± 0.16

419

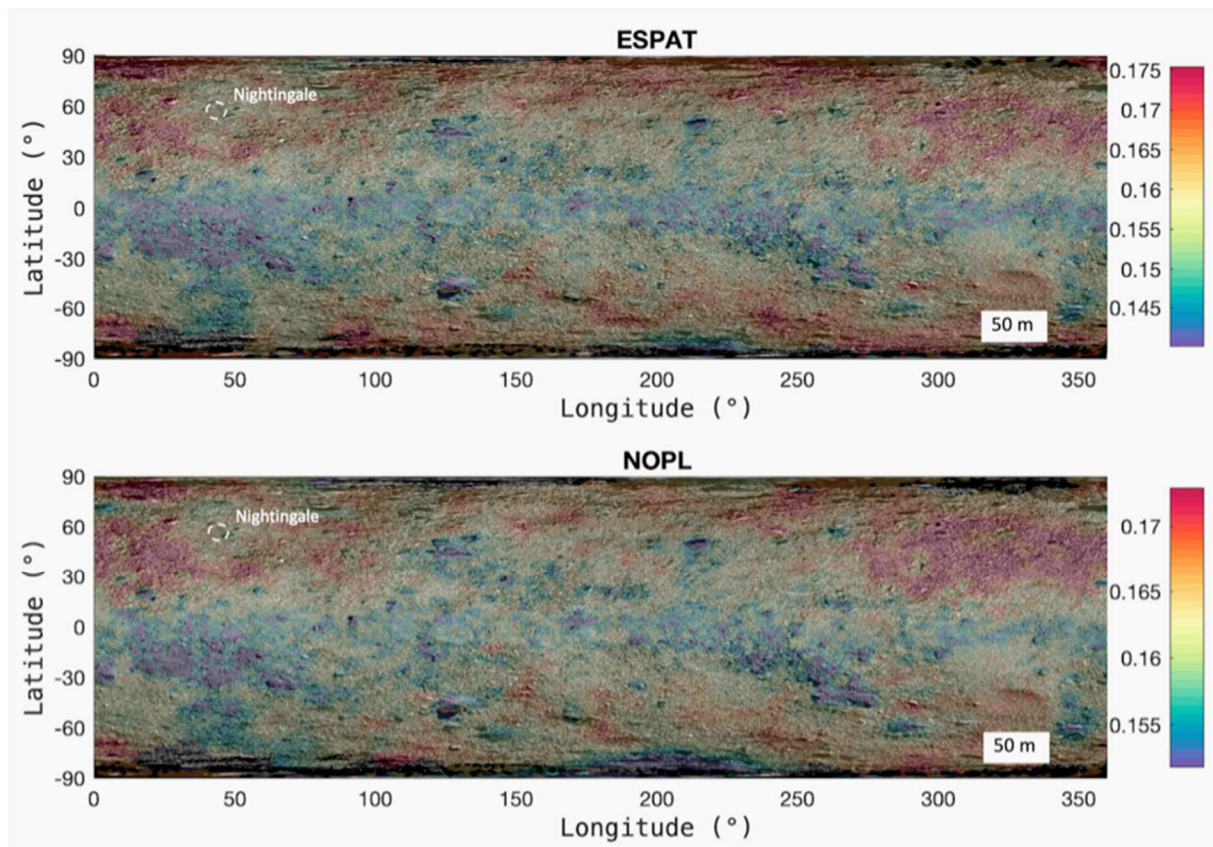
420

421 **3.2 Hydration Variations**

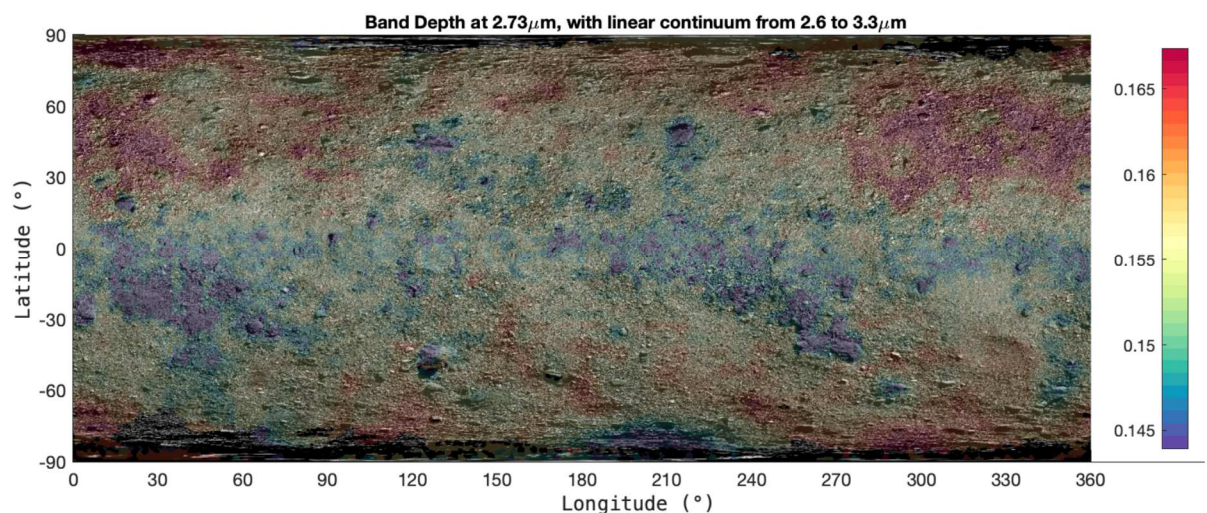
422 Maps showing the spatial variation of the NOPL and ESPAT parameters are shown in **Figure**
 423 **3a** and **3b**, overlain on the global basemap of Bennu constructed from PolyCam images
 424 (Bennett et al., 2020). Both maps show a global pattern that is very similar to the hydration
 425 band depth map (Simon et al., 2020a) that we independently computed (**Figure 4**).

426 Variations in the calculated spectral parameters are associated with albedo (DellaGiustina
 427 and Emery et al., 2019; Simon et al., 2020a) and morphological features on Bennu’s surface.
 428 We find that Bennu’s boulder-rich areas (Walsh et al., 2019) are characterized by lower NOPL
 429 and lower ESPAT. The equatorial band (-20° to 20° latitude) also shows lower NOPL and
 430 lower ESPAT. On the other hand, higher latitudes (low to intermediate boulder abundances)
 431 show higher values of NOPL and ESPAT (**Figure 3a** and **3b**). The ESPAT and NOPL maps show
 432 similar behaviour to the band depth (**Figure 4**), surface temperature, and albedo (Simon et
 433 al., 2020a). Simon et al. (2020a) report that the causes of the correlation between band
 434 depth and surface temperature are not **clear**, as **they could be due to** thermal tail removal
 435 method **or they could** be a function of surface properties (e.g., grain size effect, boulder
 436 thermal inertial, albedo, weathering, and composition) varying together.

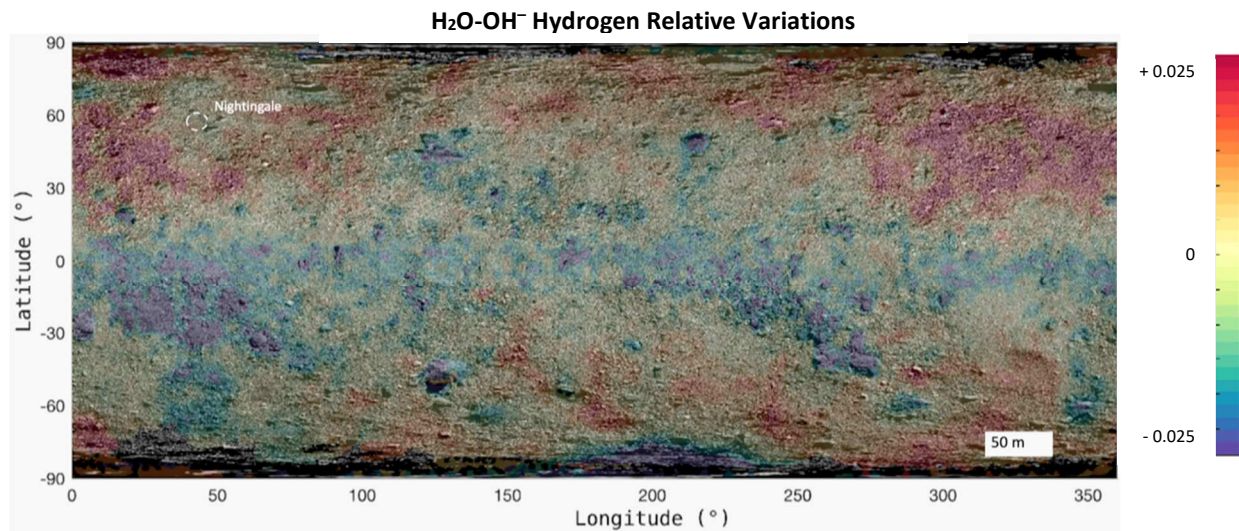
437



438
 439 **Figure 3:** The ESPAT (**top**) and NOPL (**bottom**) parameters calculated for EQ3 spectra are
 440 respectively mapped on the global basemap of Bennu (Bennett et al., 2020). The OSIRIS-REx
 441 mission's **final selected site for sampling (Nightingale)** is indicated.
 442



443 **Figure 4:** Band depth calculated at 2.73 μm , using a linear continuum from 2.6 to 3.3 μm , on
 444 EQ3 spectra (Simon et al., 2020a). **The uncertainties on the band depth are of the order of**
 445 **1% (Simon et al., 2020a).**
 446
 447
 448



449
 450 **Figure 5: The relative variation of the average H content (phylosilicate H₂O and OH group**
 451 **hydrogen content) map of Benu is derived from the average of the NOPL and ESPAT**
 452 **methods and overlain on the global basemap of Benu (Bennett et al., 2020). The zero value**
 453 **on the scale corresponds to the global average H content and the scale represent the H**
 454 **content variation with respect that zero value. The error of variation in H content is**
 455 **estimated with the error of the band depth measurement, which is of the order of 1%. The**
 456 **H content variation is in good agreement with the band depth variation (Figure 4). The**
 457 **OSIRIS-REx mission’s final selected site for sampling (Nightingale) is indicated.**
 458

459 The spatial variations of the average H content (phylosilicate H₂O and OH group hydrogen
 460 content) are overlain on the global basemap (Bennett et al., 2020) in Figure 5. The relative
 461 variation of the average H content is in agreement with the band depth variation (Figure
 462 4). Lower H content is evident in boulder-rich areas (such as from 225 to 275 degrees
 463 longitude and 0 to -60° latitude). We observe several areas—including the boulders Benben
 464 Saxum (~56 m in diameter) and Roc Saxum (~95 m), and the Tlanuwa Regio, a region with a
 465 high density of large boulders (~50 m)—that are characterized by relatively low NOPL, low
 466 ESPAT, low H content (~0.66 wt.%), and shallow 2.7- μ m band depths (Simon et al., 2020a).
 467

468 In the equatorial band (-20° to 20° latitude), the H content is lower than average. This
 469 equatorial region is characterized by rubble-filled craters and a few boulders. Other workers
 470 have shown that the equatorial band has a higher thermal inertia than global average
 471 (Rozitis et al., 2020a), a stronger red spectral slope than global average (Barucci et al., 2020;
 472 Clark et al., 2019; Fornasier et al., 2020; Simon et al., 2020a), and a shallower hydration
 473 band depth (Simon et al., 2020a). The causes of these differences in the equatorial region
 474 may include space weathering, surface roughness variations due to mass movement (Barucci
 475 et al., 2020; Jawin et al., 2020), and/or preferential fall-back of particles ejected from
 476 Benu’s surface (McMahon et al. 2020).
 477

478 We also find areas at intermediate to high latitudes (beyond 20° and -30°) that display
 479 deeper than average 2.7- μ m band depths and higher than average ESPAT and NOPL values.
 480 These areas show the most hydration, with a higher than average H content of ~0.74 wt. %
 481 (see Figure 5, particularly at longitudes 0–100° and 275–360°). There are intermediate-size

482 boulders in these regions, and the surface has a higher than average albedo at 0.55 μm and
483 lower abundances of the organic carbon surface components (Simon et al., 2020a). The **site**
484 **from which the OSIRIS-REx spacecraft collected a sample**, Nightingale (56.0° N and 42.1° E),
485 lies within this region, suggesting that the spacecraft is very likely to return a sample with
486 relatively high H content in comparison to average Bennu, yet not as high as CIs.

487

488 **4. Discussion**

489 **4.1 Spatial distribution of hydrogen**

490 The patterns of high and low hydration on Bennu's surface likely reflect early processes on
491 Bennu's parent body, as well as on-going modification of Bennu by space weathering,
492 heating, and the drivers (meteoroid impacts, thermal fracturing, and/or dehydration of
493 phyllosilicates) of the particle ejection events observed by the OSIRIS-REx mission
494 (Hergenrother et al., 2020; Lauretta and Hergenrother et al., 2019). Some of these processes
495 reduce hydration (e.g., impact-induced heating can cause dehydration, Nakamura, 2006),
496 and others may increase the H⁺ ions on the surface (e.g., solar wind implantation, Li and
497 Milliken, 2017; Tucker et al., 2019). Solar wind implantation of hydrogen has been shown to
498 increase the 2.7- μm signature diurnally on the Moon, with higher hydrogen content at
499 higher latitudes (Li and Milliken, 2017; **Clark, 2009; Pieters et al., 2009; Sunshine et al.,**
500 **2009**). A similar spatial pattern of higher hydration at the poles is seen on Bennu, though it
501 has not been noted on Ryugu (Kitazato et al., 2019). There is a strong relationship between
502 observed hydration and temperature (Simon et al., 2020a), which is also the case for the
503 implanted hydrogen on the Moon (Li and Milliken, 2017). Solar wind implantation is a
504 surface process, meaning that our findings may not be representative of unexposed material
505 on Bennu. **The lunar surface spectral data, acquired in 2017 by OVIRS, showed the 2.8 μm**
506 **absorption band (Simon et al., 2019), which is consistent with the previous full-disk**
507 **observations.**

508 Further, meteoroid bombardment would preferentially affect the equatorial region (Bottke
509 et al., 2020) and could trigger a dehydration reaction; larger impacts in the equatorial region
510 (as evidenced by the presence of large craters) could also have dehydrated material in the
511 past. Boulders exposed for longer periods of time may also be more likely to experience
512 similar dehydration processes. **Moreover, Jawin et al. (2020), analysing Bennu's surface**
513 **morphology, concluded that mass movement appears to dominantly move from the mid-**
514 **latitudes toward the equator, consequently altering the surface.**

515

516 Dehydration from impacts and implantation of H⁺ by solar wind may together explain the
517 **small spatial variation in estimated H content at the spatial resolution of the studied**
518 **spectra of Bennu (20 × 30 m). According to the modeling of Starukhina (2001), solar wind**
519 **proton implantation may result in the creation of bands, but this is not confirmed in the**
520 **spectroscopic survey of asteroids (Rivkin et al., 2003, 2015). Brunetto et al. (2020) showed**
521 **that there is likely a solar wind contribution in the OTES data of Bennu's surface when they**
522 **compared them with laboratory-irradiated meteorite spectra in the far infrared. Thus, we**
523 **can expect a contribution from the solar wind proton implantation in the 2.7- μm region.**
524 **However, spectral effects of space weathering are highly dependent on the initial physical**
525 **and compositional properties of the material as shown by Lantz et al. (2018). Lantz et al.**
526 **(2017) studied spectral effects associated with solar wind space weathering on**
527 **carbonaceous chondrites and showed the 2.7- μm absorption band minimum position**
528 **shifts to longer wavelength. Moreover, from spectral analysis of higher spatial resolution**

529 **OVIRS data of 45 craters on Bennu (Deshapriya et al., 2021), the 2.7- μ m absorption band**
530 **minimum position was found to have shifted to shorter wavelength for 20 craters with**
531 **respect to the global average band minimum position, which has been attributed to the**
532 **presence of less space-weathered (fresher) material in those craters. At the spatial**
533 **resolution of the OVIRS spectral data set used in this study, the 2.7- μ m band minimum**
534 **position does not vary. Thus, with this analyzed spectral data set and because of the lack**
535 **of supporting laboratory data, we cannot yet isolate the likely contribution of solar wind**
536 **hydrogen implantation on Bennu's surface.**

537
538 Another consideration is differences in hydration originally inherited from the parent body
539 of Bennu. The two main boulder types on Bennu, **which are well-mixed at all observed**
540 **spatial scales**, may have had different initial compositions (e.g., resulting from spatially
541 varying alteration) (Kaplan et al., 2020) and subsequent different reactions to space
542 weathering (DellaGiustina et al., 2020). We find that regions with higher 0.55- μ m reflectance
543 on Bennu (**Figure 3D in Simon et al., 2020a**) generally have more hydrogen, **though**
544 **variations are small (Figure 5)**. In addition, the largest boulders on Bennu are dark ($\leq 4.9\%$
545 albedo; DellaGiustina et al., 2020) and are associated with lower hydration, as well as
546 shallower band depth (Simon et al., 2020a), which suggests that some of the hydration
547 signature is inherent to the discrete boulder population and likely reflects a dichotomy on
548 Bennu's parent asteroid. From our dataset, we cannot separate the effects of space
549 weathering, impact dehydration, or original composition.

550
551

552 **4.2 Hydrogen abundance and comparison to meteorites**

553 Bennu has similar H content (0.71 ± 0.16 wt.%) to the ranges found in CM meteorites (0.46–
554 1.36 wt%), the ungrouped C2 meteorite Tagish Lake (0.50–0.69 wt.%), and CR meteorites
555 (0.30–1.20 wt.%, Alexander et al., 2012). However, previous spectral analyses ruled out the
556 CRs as analogs for Bennu and suggested that Bennu is most similar to the most aqueously
557 altered CM and CI chondrites (Hamilton et al., 2019). However the H content of Bennu is not
558 similar to those of the CIs (1.330–1.366 wt.%, Alexander et al., 2012, **Figure 2**).

559

560 Our results therefore indicate that Bennu is most similar to the CM and Tagish Lake
561 meteorites. Most heated CMs have experienced temperatures of $> \sim 400^\circ\text{C}$ (e.g. Lee et al.,
562 2016). The estimation of H content, as shown here, and the fact that olivine has not been
563 detected on the surface by OVIRS or OTEs, both suggest that Bennu's phyllosilicates have
564 not been significantly dehydrated or decomposed, which occurs at $\sim 700^\circ\text{C}$ (Hamilton et al.,
565 2019; Hamilton et al., in revision). **The areas of lower H content on Bennu's surface**
566 **correspond to higher surface temperature (~ 350 K) as shown in Figure 3C in Simon et al.,**
567 **2020a. Moreover, Rozitis et al. (2020b), modelling Bennu's surface temperature, found**
568 **modest seasonal temperature variations but relatively high diurnal temperature with a**
569 **maximum of 390K at the equator during perihelion.**

570 The presence of organics in some locations on Bennu's surface could imply that these
571 regions have not experienced significant heating (Kaplan et al., in prep; Kebukawa et al.,
572 2010; Simon et al., 2020a), which could potentially rule out the heated CMs as analogs of
573 Bennu, without excluding the lower end of heated CMs as evidence consistent with low to
574 moderate heating are present on Bennu. Although Tagish Lake has a strongly red spectral
575 slope (unlike the moderately blue slope of Bennu), it has previously been suggested to be

576 analogous to Bennu in terms of its carbonate-rich lithology, strong hydration feature, and
577 low albedo (Kaplan et al., 2020; Merlin et al., *in revision*) as well as **by OTES comparison to**
578 **laboratory spectral data (Brunetto et al., 2020).**
579

580

581 **4.3 Hydrogen abundance and comparison with C-complex asteroids**

582 **The relative abundance of phyllosilicates on asteroid surfaces has been the subject of**
583 **studies of ground-based (Rivkin et al., 2003; Takir et al., 2019) and space-based**
584 **observations (Ammannito et al., 2016; De Sanctis et al., 2016).**

585 **Ground-based observation campaigns of asteroids revealed the presence of 2.7- μ m region**
586 **absorption band in a number of asteroids (Rivkin et al., 2003; Rivkin et al., 2015, Takir &**
587 **Emery, 2012). However, the 2.5–2.85 μ m range remains difficult to analyse due to**
588 **atmospheric absorption. The band minimum is generally situated in this wavelength**
589 **range, limiting detailed mineralogical studies and comparison with carbonaceous**
590 **chondrite.**

591

592 **The Dawn mission collected spatially resolved spectral data with near-global coverage of**
593 **Ceres' and Vesta's surfaces using the visible and infrared mapping spectrometer (VIR) (De**
594 **Sanctis et al., 2011) from 0.25 to 5 μ m. Ammannito et al. (2016) studied the repartition of**
595 **phyllosilicates on the surface of Ceres using spectral data collected by VIR. The relative**
596 **abundance of the Mg-bearing phyllosilicates was mapped using the intensity of its 2.72-to-**
597 **2.73- μ m centered absorption band and showed the variability of the Mg-bearing**
598 **phyllosilicate abundance as well as a fairly uniform phyllosilicate composition across Ceres**
599 **surface (with no significant variation of the band minimum position). Furthermore, using**
600 **the VIR spectrometer in combination with the GRaND instrument (gamma ray and neutron**
601 **detector) of the Dawn mission, Prettyman et al. (2019) analyzed the hydrogen elemental**
602 **abundance at the surface of Ceres and Vesta. Prettyman et al., found that the majority of**
603 **hydrogen is present in hydroxyl-bearing minerals at the surface of Vesta, while for Ceres,**
604 **higher concentration of hydrogen in the poles is consistent with the presence of**
605 **subsurface ice. However, the evolution histories and physical properties of these two**
606 **objects are completely dissimilar from those of Bennu.**

607

608 **Spectroscopic surveys of C-complex and S-complex asteroids were performed using the**
609 **Infrared Camera (from 2.5 to 5 μ m) on board the satellite AKARI and the resulting asteroid**
610 **spectral library was analyzed by Usui et al. (2019). They showed that the majority of**
611 **observed C-complex asteroids present a significant 2.7- μ m region absorption band,**
612 **generally centered near 2.75 μ m. They analyzed the relative abundance of hydrated**
613 **phyllosilicates with a band depth calculation. Beck et al. (2020) discussed an approach to**
614 **quantify the equivalent water abundance of main-belt asteroid surfaces using AKARI**
615 **asteroid spectral data set in coordination with a set of laboratory measurements on**
616 **carbonaceous chondrites under dry vacuum conditions (Beck et al., 2010). Using this newly**
617 **available near-infrared spectral library of C-complex main-belt asteroids, Beck et al. (2020)**
618 **computed a spectral metric and compared the results of those from laboratory-measured**
619 **carbonaceous chondrite spectra as well as carbonaceous chondrite H₂O abundances (wt.%)**
620 **estimated by TGA (thermogravimetric analyses). The spectral metric they found, which can**
621 **be applied to all meteorite types used in this study (CM, CI, CV, CR, CO, and Tagish Lake),**
622 **uses the sum of the band depths at 2.75 and 2.8 μ m. Through a linear correlation between**

623 **the previously mentioned spectral metric, they were able to estimate the water content at**
624 **the surface of C-complex main-belt asteroids and determined a water content average of**
625 **4.5 wt.% H₂O with high uncertainties of ± 4 wt.% H₂O linked to the quality of the**
626 **correlation. Beck et al. observed that the water content estimated for the most hydrated**
627 **asteroids is lower than those of carbonaceous chondrites. This may be due to space**
628 **weathering of asteroids or to an underestimation of the terrestrial water contribution in**
629 **carbonaceous chondrites. While Bennu's spectra are of higher resolution and quality than**
630 **AKARI's asteroid observations, the global H content estimation for Bennu gives only an**
631 **indication of the surface hydration without disentangling the space weathering effects on**
632 **Bennu's surface.**

633

634 **5. Conclusions**

635 These results represent the first spatially resolved estimation of hydrogen content in water
636 and hydroxyl groups of hydrated phyllosilicates of an asteroid surface, revealing the
637 presence of small latitudinal differences in H content as well as differences associated with
638 geomorphology. Our results suggest that Bennu is moderately hydrated compared to CC
639 meteorites, with an average H content of $\sim 0.71 \pm 0.16$ wt.% derived from the NOPL and
640 ESPAT methods. Long-term, on-going surface modification processes, including solar wind
641 implantation and impact dehydration, may be responsible for the lower H content in the
642 equatorial region. In addition, different initial compositions inherited from Bennu's parent
643 body (DellaGiustina et al., 2020) may play a role in the distribution of H content, as
644 exemplified by large, dark individual boulders with lower than average H content.

645

646 Quantifying the H content at the surface of Bennu **can constrain its thermal history and help**
647 **us to understand the composition of the primitive asteroid populations. The H content**
648 **variations on Bennu, the full range of which is 0.64 ± 0.15 to 0.76 ± 0.15 wt.%, are small**
649 **compared to the overall range of the CC meteorites used in this study (0.410 ± 0.001 to**
650 **1.366 ± 0.015 wt.%), which could validate the use of non-spatially resolved investigations of**
651 **the 2.7- μ m feature on asteroids to understand hydration and/or relation to the CC**
652 **meteorites (e.g., with ground- or space-based telescopes). The study of H₂O and OH⁻**
653 **abundance on many primitive bodies can help constrain models of the formation and**
654 **evolution of our Solar System, as well as some of the key processes in the development of**
655 **life on Earth (Brack, 1993).**

656 **The origin of water on Earth is one of the most important topics still debated (Alexander et**
657 **al., 2012; Altwegg et al., 2015; Piani et al., 2020), i.e. how the Earth acquired so much**
658 **water, having originated from a hot, dry part of the disk of gas and dust from which the Solar**
659 **System formed. Many primitive asteroids once contained abundant water, now stored as**
660 **OH in hydrated minerals (Alexander et al. 2012). Therefore, the H content (phyllosilicate**
661 **H₂O and OH group hydrogen content) as well as its distribution found for Bennu's surface**
662 **could help to constrain and model the compositional evolution of the pristine asteroid**
663 **population.**

664

665 Two of the key ingredients for life, water and complex organic molecules, may have been
666 delivered to Earth after formation by impacts with small bodies (Altwegg et al., 2019).
667 OSIRIS-REx sampled Bennu's surface at site Nightingale in October 2020 and will return the
668 collected sample to Earth in 2023; **the sample is predicted to contain water and organics. As**
669 **Beck et al. (2021) estimated the water content for the most hydrated asteroids to be lower**

670 **than those of carbonaceous chondrites, we** suggest that the **hydrogen content contained in**
671 **the phyllosilicate H₂O and OH group** of the returned sample will be at least 0.71 wt.%. This
672 hydrogen abundance is similar to those of the CM and Tagish Lake meteorites, which share
673 similarities in phyllosilicate mineralogy with Benu. **Our analysis does not allow to unravel**
674 **the space weathering effects on Benu's surface.**

675 Both the sample and the VNIR spectral data reflect the surface composition of Benu, which
676 may be more heated and/or space-weathered than material sourced from the interior.

677 **Given that the OSIRIS-REx sample acquisition mechanism penetrated several centimetres**
678 **into the subsurface (Lauretta et al., 2021),** weathered as well as potentially unweathered
679 material will be returned. Our results, if validated by analysis of the returned sample, could
680 be used to estimate H content on other hydrated asteroids.

681
682
683

684 **Acknowledgments**

685 We are grateful to the entire OSIRIS-REx Team for making the encounter with Benu
686 possible. This material is based upon work supported by NASA under Contract NNM10AA11C
687 issued through the New Frontiers Program. French authors thank the French Space Agency
688 CNES for financial support. PHH acknowledges funding support by DIM ACAV+ program by
689 the region Ile de France. GP and JRB acknowledge support from the INAF – Astrophysical
690 Observatory of Arcetri, which is supported by the Italian Space Agency agreement no 2017-
691 37-H.0. This research uses spectra acquired at the NASA RELAB facility at Brown University.

692 **We thank Catherine Wolner for editorial help. We thank the two anonymous referees for**
693 **their comments and suggestions that helped improving this manuscript.**

694
695
696

697 **Data availability**

698 The OVIRS EQ3 spectral data used in this work are available via the Planetary Data System at
699 <https://sbn.psi.edu/pds/resource/orex/ovirs.html>. Data are delivered to the PDS according
700 to the OSIRIS-REx Data Management Plan available in the OSIRIS-REx PDS archive. **The maps**
701 **are available upon request.** The meteorite data were obtained from the references shown
702 in **Appendix A.**

703
704
705
706
707
708
709
710
711
712
713
714
715
716

717 **References**

- 718 - Alexander C.M.O'D., Fogel M.L., Yabuta H., Cody G.D., 2007. The origin and evolution of
719 chondrites recorded in the elemental and isotopic compositions of their macromolecular
720 organic matter. *Geochim. Cosmochim. Acta* 71(17), 4380-4403.
721
- 722 - Alexander C.M.O'D., Bowden R., Fogel M.L., Howard K.T., Herd C.D.K., Nittler L.R., 2012.
723 The Provenances of Asteroids, and Their Contributions to the Volatile Inventories of the
724 Terrestrial Planets. *Science* 337, 721-723.
725
- 726 - Alexander C.M.O'D., Howard K.T., Bowden R., Fogel M.L., 2013. The classification of CM
727 and CR chondrites using bulk H, C and N abundances and isotopic compositions.
728 *Geochim. Cosmochim. Acta* 123, 244-260.
729
- 730 - **Altwegg, K., et al., 2015. 67P/Churyumov-Gerasimenko, a Jupiter family comet with a**
731 **high D/H ratio. *Science* 347.6220, doi: 10.1126/science.1261952**
732
- 733 - Altwegg, K., Balsiger, H., Fuselier, S. A., 2019. Cometary chemistry and the origin of icy
734 solar system bodies: the view after Rosetta. *Annual Rev. Astron. Astrophys.* 57, 113-155.
735
- 736 - **Ammannito, E., et al., 2016. Distribution of phyllosilicates on the surface of Ceres.**
737 ***Science* 353.6303, doi: 10.1126/science.aaf4279**
738
- 739 - **Amsellem, E., Moynier, F., Mahan, B., Beck, P., 2020. Timing of thermal metamorphism**
740 **in CM chondrites: Implications for Ryugu and Bennu future sample return. *Icarus*, 339,**
741 **113593.**
742
- 743 - Barnouin, O.S., et al., 2019. Shape of (101955) Bennu indicative of a rubble pile with
744 internal stiffness. *Nat. Geosci.* 12(4), 247-252.
745
- 746 - Barucci, M.A., et al., 2020. OSIRIS-REx spectral analysis of (101955) Bennu by
747 multivariate Statistics, *Astron. Astrophys.* 637, L4.
748
- 749 - Beck, P., et al., 2010. Hydrous mineralogy of CM and CI chondrites from infrared
750 spectroscopy and their relationship with low albedo asteroids. *Geochim. Cosmochim.*
751 *Acta* 74(16), 4881-4892.
752
- 753 - **Beck, P., et al., 2020. "Water" abundance at the surface of C-complex main-belt**
754 **asteroids. *Icarus*, 114125.**
- 755 - Bennett, C., et al., 2021. A High-Resolution Global Basemap of (101995) Bennu. *Icarus*
756 375, 113690.
- 757 - **Bishop, J., Murad, E., Dyar, M. D., 2002. The influence of octahedral and tetrahedral**
758 **cation substitution on the structure of smectites and serpentines as observed through**
759 **infrared spectroscopy. *Clay Minerals*, 37(4), 617-628.**
760
- 761 - Bottke, W.F., et al., 2015. In search of the source of asteroid (101955) Bennu:
762 applications of the stochastic YORP model. *Icarus* 247, 191-217.

- 763
764 - Bottke, W.F., Moorhead, A., Connolly, H.C. Jr, 2020. Meteoroid Impacts as a Source of
765 Bennu's Particle Ejection Events. *J. Geophys. Res. – Planets*, doi: 10.1029/2019JE006282.
766
- 767 - Brack, A., 1993. Liquid water and the origin of life. *Origins of Life and Evolution of the*
768 *Biosphere* 23(1), 3-10.
769
- 770 - **Brunetto, R., et al., 2020. Characterizing irradiated surfaces using IR spectroscopy."**
771 ***Icarus* 345, 113722.**
772
- 773 - **Clark, R. N., King, T. V. V., Klejwa, M., Swayze, G. A., Vergo, N., 1990. High spectral**
774 **resolution reflectance spectroscopy of minerals, *J. Geophys. Res.*, 95(B8), 12653–**
775 **12680, doi:10.1029/JB095iB08p12653.**
- 776 - Clark, R.N., 1999. Spectroscopy of rocks and minerals, and principles of spectroscopy.
777 *Manual of remote sensing* 3(3-58), 2-2.
- 778 - **Clark, R.N., 2009. Detection of adsorbed water and hydroxyl on the Moon. *Science* 326**
779 **(5952), 562-564, doi:10.1126/science.1178105.**
- 780 - Clark, B.E., et al., 2010. Spectroscopy of B-type asteroids: Subgroups and meteorite
781 analogs. *J. Geophys. Res. – Planets*, 115(E6).
- 782 - Clark, B.E., et al., 2011. Asteroid (101955) 1999 RQ36: Spectroscopy from 0.4 to 2.5µm
783 and Meteorite Analogs. *Icarus* 216, 462-475.
- 784 - Daly, M.G., et al., 2020. Hemispherical Differences in the Shape and Topography of
785 Asteroid (101955) Bennu. *Science Advances*, doi: 10.1126/sciadv.abd3649.
786
- 787 - DellaGiustina, D.N., Emery, J.P., et al., 2019. Properties of rubble-pile asteroid (101955)
788 Bennu from OSIRIS-REx imaging and thermal analysis. *Nat. Astron.*, 3(4), 341-351.
789
- 790 - DellaGiustina, D.N., et al., 2020. Variations in Color and Reflectance of Asteroid (101955)
791 Bennu. *Science*, doi: 10.1126/science.abc3660.
792
- 793 - **De Sanctis, M.C., et al., 2011. The VIR spectrometer. *Space Science Reviews* 163, 329-**
794 **369.**
795
- 796 - **De Sanctis, M.C., et al., 2016. Bright carbonate deposits as evidence of aqueous**
797 **alteration on (1) Ceres. *Nature*, 536(7614), 54-57.**
- 798 - De Sanctis, M.C., et al., 2017. Localized aliphatic organic material on the surface of Ceres.
799 *Science*, 355(6326), 719-722.
- 800 - **Farmer, V.C., 1974. Infrared spectra of minerals. Mineralogical society.**
801
- 802 - **Ferrone, S., et al., 2021. Analysis of Projection Effects in OSIRIS-REx Spectral Mapping**
803 **Methods: Recommended Protocols for Facet-Based Mapping. *Earth Space Science*, doi:**
804 **10.1029/2019EA000613**

- 805 - Fornasier, S., Lazzarin, M., Barbieri, C., Barucci, M.A., 1999. Spectroscopic comparison of
806 aqueous altered asteroids with CM2 carbonaceous chondrite meteorites. *Astron.*
807 *Astrophys. Suppl. Ser.*, 135(1), 65-73.
- 808 - **Fornasier, S., et al., 2020. Phase reddening on asteroid Bennu from visible and near-**
809 **infrared spectroscopy. *Astron. Astrophys.* 644, A142, [https://doi.org/10.1051/0004-](https://doi.org/10.1051/0004-6361/202039552)**
810 **6361/202039552 .**
- 811 - Garenne, A., et al., 2016. Bidirectional reflectance spectroscopy of carbonaceous
812 chondrites: Implications for water quantification and primary composition. *Icarus* 264,
813 172-183.
- 814
- 815 - Gilmour, C.M., Herd, C. D. K., Beck, P., 2019. Water abundance in the Tagish Lake
816 meteorite from TGA and IR spectroscopy: Evaluation of aqueous alteration. *Meteorit.*
817 *Planet. Sci.* 54, 1951–1972.
- 818 - Hamilton, V.E., et al., 2019. Evidence for widespread hydrated minerals on asteroid
819 (101955) Bennu. *Nat. Astron.* 3(4), 332-340.
- 820 - **Hamilton, V. E. et al. (in revision). Evidence for limited compositional and particle size**
821 **variation on asteroid (101955) Bennu from thermal infrared spectroscopy. *Astron.***
822 ***Astrophys.***
- 823 - Hapke, B., 1993. *Theory of Reflectance and Emittance Spectroscopy.* Cambridge
824 University Press, Cambridge, UK.
- 825 - Hapke, B., 2002. Bidirectional reflectance spectroscopy: 5. The coherent backscatter
826 opposition effect and anisotropic scattering. *Icarus* 157(2), 523-534.
- 827 - Helfenstein, P., Shepard, M.K., 2011. Testing the Hapke photometric model: Improved
828 inversion and the porosity correction. *Icarus* 215(1), 83-100.
- 829 - Hergenrother, C.W., et al., 2020. Introduction to the Special Issue: Exploration of the
830 Activity of Asteroid (101955) Bennu. *J. Geophys. Res. – Planets*, doi:
831 10.1029/2020JE006549.
- 832 - Howard, K.T., Alexander, C.M.O.'D., Schrader, D.L., Dyl, K.A., 2015. Classification of
833 hydrous meteorites (CR, CM and C2 ungrouped) by phyllosilicate fraction: PSD-XRD
834 modal mineralogy and planetesimal environments. *Geochim. Cosmochim. Acta* 149, 206-
835 222.
- 836 - Jawin, E.R. et al., 2020. Global patterns of recent mass movement on asteroid (101955)
837 Bennu. *J. Geophys. Res. – Planets*, doi: 10.1029/2020JE006475.
- 838
- 839 - Jutzi, M., Michel, P., 2020. Collisional heating and compaction of small bodies:
840 constraints for their origin and evolution. *Icarus*, 113867.

- 841 - Kaplan, H.H., Milliken, R.E., Alexander, C.M.O.'D., Herd, C.D., 2019. Reflectance
842 spectroscopy of insoluble organic matter (IOM) and carbonaceous meteorites. *Meteorit.*
843 *Planet. Sci.* 54(5), 1051-1068.
- 844 - Kaplan, H.H., et al., in prep. Composition of Organics on Asteroid (101955) Bennu.
845 *Astron. Astrophys.*
- 846
847 - Kaplan, H.H., et al., 2020. Bright carbonate veins on asteroid (101955) Bennu:
848 Implications for aqueous alteration history. *Science* doi: 10.1126/science.abc3557.
- 849
850 - Kebukawa, Y., Nakashima, S. Zolensky, M.E., 2010. Kinetics of organic matter degradation
851 in the Murchison meteorite for the evaluation of parent-body temperature history:
852 Kinetics of organic matter degradation in the Murchison meteorite. *Meteorit. Planet. Sci.*
853 45, 99–113.
- 854
855 - Kitazato, K., et al., 2019. The surface composition of asteroid 162173 Ryugu from
856 Hayabusa2 near-infrared spectroscopy. *Science* 364(6437), 272-275.
- 857
858 - **Lantz, C., et al., 2017. Ion irradiation of carbonaceous chondrites: A new view of space**
859 **weathering on primitive asteroids. *Icarus* 285, 43-57.**
- 860
861 - **Lantz, C., Binzel, R.P., DeMeo, F.E., 2018. Space weathering trends on carbonaceous**
862 **asteroids: A possible explanation for Bennu's blue slope? *Icarus* 302, 10-17.**
- 863
864 - Lauretta, D.S., et al., 2017. OSIRIS-REx: sample return from asteroid (101955) Bennu.
865 *Space Sci. Rev.* 212(1-2), 925-984.
- 866
867 - Lauretta, D.S., Hergenrother, C.W. et al., 2019. Episodes of particle ejection from the
868 surface of the active asteroid (101955) Bennu. *Science*, doi: 10.1126/science.aay3544.
- 869
870 - **Lauretta, D. S., et al., 2021. THE OSIRIS-REX TOUCH-AND-GO SAMPLE ACQUISITION**
871 **EVENT AND IMPLICATIONS FOR THE NATURE OF THE RETURNED SAMPLE. 52nd Lunar**
872 **and Planetary Science Conference.**
- 873 - Lee, M.R., Lindgren, P., King, A.J., Greenwood, R.C., Franchi, I.A., Sparkes, R., 2016.
874 Elephant Moraine 96029, a very mildly aqueously altered and heated CM carbonaceous
875 chondrite: Implications for the drivers of parent body processing. *Geochim. Cosmochim.*
876 *Acta* 187, 237-259.
- 877 - Li, J.Y., et al., 2007a. Deep Impact photometry of comet 9P/Tempel 1. *Icarus* 187(1), 41-
878 55.
- 879 - Li, J.Y., A'Hearn, M.F., McFadden, L.A., Belton, M.J., 2007b. Photometric analysis and
880 disk-resolved thermal modeling of Comet 19P/Borrelly from Deep Space 1 data. *Icarus*
881 188(1), 195-211.
- 882 - Li, J.Y., A'Hearn, M.F., Farnham, T.L., McFadden, L.A., 2009. Photometric analysis of the
883 nucleus of Comet 81P/Wild 2 from Stardust images. *Icarus* 204(1), 209-226.

- 884 - Li, J.Y., et al., **in revision**. Spectrophotometric modeling and mapping of (101955) Bennu
885 and the implications. *Planet. Sci. J.*
- 886 - Li, S., Milliken, R.E., 2017. Water on the surface of the Moon as seen by the Moon
887 Mineralogy Mapper: Distribution, abundance, and origins. *Science Advances* 3(9),
888 e1701471.
- 889 - **Manceau A. et al., 2000. Oxidation-reduction mechanism of iron in dioctahedral**
890 **smectites: II. Crystal chemistry of reduced Garfield nontronite. *American Mineralogist*,**
891 **Volume 85, pages 153–172.**
- 892 - McMahon, J.W., et al., 2020. Dynamical Evolution of Simulated Particles Ejected from
893 Asteroid Bennu. *J. Geophys. Res. – Planets*, e2019JE006229.
- 894 - **McSween Jr, H. Y., 1979. Alteration in CM carbonaceous chondrites inferred from**
895 **modal and chemical variations in matrix. *Geochimica et Cosmochimica Acta*, 43(11),**
896 **1761-1770.**
- 897
898 - McSween, H.Y. Jr, et al., 2018. Carbonaceous chondrites as analogs for the composition
899 and alteration of Ceres. *Meteorit. Planet. Sci.* 53(9), 1793-1804.
- 900
901 - Merlin, F., et al., **in revision**. In search of Bennu analogs: Hapke modeling of meteorite
902 mixtures. *Astron. Astrophys.*
- 903
904 - Michel, P., Ballouz, R.-L., et al., 2020. Collisional formation of top-shaped asteroids and
905 implications for the origins of Ryugu and Bennu. *Nat. Comm.*, doi: 10.1038/s41467-020-
906 16433-z.
- 907
908 - Milliken R.E., Mustard J.F., 2005. Quantifying absolute water content of minerals using
909 near-infrared reflectance spectroscopy. *J. Geophys. Res.* 110, E12001,
910 doi:10.1029/2005JE002534, 2005
- 911
912 - Milliken, R.E., Mustard, J.F., 2007. Estimating the water content of hydrated minerals
913 using reflectance spectroscopy: II. Effects of particle size. *Icarus*, 189(2), 574-588.
- 914
915 - Milliken R.E., et al., 2007. Hydration state of the Martian surface as seen by Mars Express
916 OMEGA: 2. H₂O content of the surface. *J. Geophys. Res.* 112, E08S07, doi:
917 10.1029/2006JE002853
- 918
919 - Mustard, J.F., et al., 2008. Hydrated silicate minerals on Mars observed by the Mars
920 Reconnaissance Orbiter CRISM instrument. *Nature* 454(7202), 305-309.
- 921
922 - Nakamura, T.Y., 2006. 793321 CM chondrite: Dehydrated regolith material of a hydrous
923 asteroid. *Earth Planet. Sci. Lett.* 242, 26–38.
- 924
925 - **Piani, L., Marrocchi, Y., Rigaudier, T., Vacher, L.G., Thomassin, D., Marty, B., 2020.**
926 **Earth’s water may have been inherited from material similar to enstatite chondrite**
927 **meteorites. *Science*, 369(6507), 1110-1113.**

- 928
- 929 - **Pieters, C.M., et al., 2009. Character and spatial distribution of OH/H₂O on the surface**
- 930 **of the Moon seen by M3 on Chandrayaan-1. *Science*, 326(5952), 568-572.**
- 931
- 932 - **Pommerol, A., Schmitt, B., 2008a. Strength of the H₂O near-infrared absorption bands**
- 933 **in hydrated minerals: Effects of measurement geometry. *J. Geophys. Res. Planets*,**
- 934 **113(E12).**
- 935
- 936 - **Pommerol, A., Schmitt, B., 2008b. Strength of the H₂O near-infrared absorption bands**
- 937 **in hydrated minerals: Effects of particle size and correlation with albedo. *J. Geophys.***
- 938 ***Res. Planets*, 113(E10).**
- 939
- 940 - Potin, S., Beck., P., Usui, F., Bonal, L., Vernazza, P., Schmitt, B., 2020. Style and intensity
- 941 of hydration among C-complex asteroids: a comparison to desiccated carbonaceous
- 942 chondrites. *Icarus* 348, 113826.
- 943
- 944 - **Prettyman, T.H., et al., 2019. Elemental composition and mineralogy of Vesta and**
- 945 **Ceres: Distribution and origins of hydrogen-bearing species. *Icarus* 318, 42-55.**
- 946
- 947 - Reuter, D.C., et al., 2018. The OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS):
- 948 spectral maps of the asteroid Bennu. *Space Sci. Rev.* 214(2), 54.
- 949
- 950 - **Rivkin, A.S., et al., 2003. Hydrogen concentrations on C-class asteroids derived from**
- 951 **remote sensing. *Meteoritics & Planetary Science* 38, Nr 9, 1383–1398.**
- 952
- 953 - Rivkin A.S., et al., 2015. Water and Hydroxyl on Asteroids. *Asteroids IV* (P. Michel et al.,
- 954 eds), 65-87. Univ. of Arizona Press, Tucson.
- 955
- 956 - **Robert, F., Epstein, S., 1982. The concentration and isotopic composition of hydrogen,**
- 957 **carbon and nitrogen in carbonaceous meteorites. *Geochim. Cosmochim. Acta* 46, 81-**
- 958 **95.**
- 959
- 960 - Rozitis, B., et al., 2020a. Asteroid (101955) Bennu's Weak Boulders and Thermally
- 961 Anomalous Equator. *Science Advances*, doi: 10.1126/sciadv.abc3699.
- 962
- 963 - **Rozitis, B., et al., 2020b. Implications for ice stability and particle ejection from high-**
- 964 **resolution temperature modeling of asteroid (101955) Bennu. *J. Geophys. Res. Planets*,**
- 965 **125, e2019JE006323. <https://doi.org/10.1029/2019JE006323>**
- 966
- 967 - Rubin, A.E., Trigo-Rodríguez, J.M., Huber, H., Wasson, J.T., 2007. Progressive aqueous
- 968 alteration of CM carbonaceous chondrites. *Geochim. Cosmochim. Acta* 71, 2361-2382.
- 969
- 970 - **Ryskin, Y.I., 1974. The vibrations of protons in minerals: hydroxyl, water and**
- 971 **ammonium. *The infrared spectra of minerals*, 137-182.**
- 972
- 973 - Simon, A.A., et al., 2018. In-Flight Calibration and Performance of the OSIRIS-REx Visible
- and IR Spectrometer (OVIRS). *Remote Sensing*, doi: 10.3390/rs10091486.

- 974 - **Simon, A.A., et al., 2019. OSIRIS-REx visible and near-infrared observations of the**
975 **Moon. Geophysical Research Letters, 46, 6322–6326. [https://](https://doi.org/10.1029/2019GL083341)**
976 **doi.org/10.1029/2019GL083341.**
- 977 - Simon, A.A., et al., 2020a. Widespread carbon-bearing materials on near-Earth asteroid
978 (101955) Bennu. *Science*, doi: 10.1126/science.abc3522.
- 979
- 980 - **Simon, A.A., et al., 2020b. Weak spectral features on (101995) Bennu from the OSIRIS-**
981 **REx Visible and InfraRed Spectrometer. *Astron. Astrophys.* 644, A148.**
- 982
- 983 - **Starukhina, L., 2001. Water detection on atmosphereless celestial bodies: Alternative**
984 **explanations of the observations. *J. Geophys. Res. Planets*, 106(E7), 14701-14710.**
- 985
- 986 - **Sunshine, J.M., et al., 2009. Temporal and spatial variability of lunar hydration as**
987 **observed by the Deep Impact spacecraft. *Science*, 326(5952), 565-568.**
- 988 - Takir, D., et al., 2013. Nature and degree of aqueous alteration in CM and CI
989 carbonaceous chondrites. *Meteorit. Planet. Sci.* 48(9), 1618-1637.
- 990 - **Takir, D., Emery, J. P., 2012. Outer main belt asteroids: Identification and distribution**
991 **of four 3- μ m spectral groups. *Icarus*, 219(2), 641-654.**
- 992 - Takir, D., Emery, J.P., McSween, H.Y. Jr, 2015. Toward an understanding of phyllosilicate
993 mineralogy in the outer main asteroid belt. *Icarus* 257, 185-193.
- 994 - Takir, D., Stockstill-Cahill, K.R., Hibbitts, C.A., Nakauchi, Y., 2019. 3- μ m reflectance
995 spectroscopy of carbonaceous chondrites under asteroid-like conditions. *Icarus* 333,
996 243–251.
- 997
- 998 - Tucker, O.J., Farrell, W.M., Killen, R.M., Hurley, D.M., 2019. Solar Wind Implantation Into
999 the Lunar Regolith: Monte Carlo Simulations of H Retention in a Surface With Defects
1000 and the H₂ Exosphere. *J. Geophys. Res. Planets* 124, 278–293.
- 1001
- 1002 - **Usui, F., Hasegawa, S., Ootsubo, T., Onaka, T., 2019. AKARI/IRC near-infrared asteroid**
1003 **spectroscopic survey: AcuA-spec. *Publ. Astron. Soc. Japan* 71 (1), 1 (1–41), doi:**
1004 **[10.1093/pasj/psy125](https://doi.org/10.1093/pasj/psy125).**
- 1005
- 1006 - Walsh, K.J., Delbó, M., Bottke, W.F., Vokrouhlický, D., Lauretta, D.S., 2013. Introducing
1007 the Eulalia and new Polana asteroid families: Re-assessing primitive asteroid families in
1008 the inner Main Belt. *Icarus* 225(1), 283-297.
- 1009
- 1010 - Walsh, K.J., et al., 2019. Craters, boulders and regolith of (101955) Bennu indicative of an
1011 old and dynamic surface. *Nat. Geosci.* 12(4), 242-246.
- 1012
- 1013 - Zou, X.-D., et al., **2021. Photometry of asteroid (101955) Bennu with OVIRS on OSIRIS-**
1014 **REx. *Icarus* 358, 114183, doi.org/10.1016/j.icarus.2020.114183.**
- 1015
- 1016

1017 **Appendix A:** The selected meteorites are reported with their spectral reference and their H
1018 content calculated by Alexander et al., 2012, 2013 (*); Garenne et al., 2016 (**); Gilmore et
1019 al., 2019 (***). For each meteorite, the type and the subtype using the Rubin (2007) scale
1020 are reported, as well as the ones for which a Gaussian centered originally at 2.75 μ m was
1021 modelled (¹).

Name	H content	H error	Types	Subtypes	Spectrum Reference	H content Reference
ALH83100	1,353	0,009	CM1/2	2.1	Garenne et al., 2016	*
ALH83100 ¹	1,353	0,009	CM1/2	2.1	Potin et al., 2020	*
ALH84029	1,260	0,009	CM1/2	2.1	Garenne et al., 2016	*
ALH84033	0,610	0,018	CM2 Heated	/	Garenne et al., 2016	*
ALH84044	1,240	0,008	CM2	2.1	Garenne et al., 2016	*
Banten ¹	0,910	0,010	CM2	2.5	Takir et al., 2019	*
Cold Bokkeveld (*) ¹	1,220	0,004	CM2	2.2	Takir et al., 2013	*
DOM03183	0,950	0,001	CM2 Heated	2.3	Garenne et al., 2016	*
DOM08003 ¹	1,359	0,006	CM2	2.2	Potin et al., 2020	*
EET83355	0,410	0,001	CM2 Heated	/	Garenne et al., 2016	*
EET96029	0,728	0,012	CM2 Heated	/	Garenne et al., 2016	*
EET96029 ¹	0,728	0,012	CM2 Heated	/	Potin et al., 2020	*
Essebi (*) ¹	0,770	0,005	CM2?	/	Takir et al., 2019	*
Ivuna ¹	1,330	0,094	CI1	/	Takir et al., 2013	*
LAP02277 ¹	1,112	0,009	CM1 Heated	2.0	Takir et al., 2013	*
LAP02333	1,020	0,005	CM2	2.6	Garenne et al., 2016	*
LAP02336	0,950	0,005	CM2	2.6	Garenne et al., 2016	*
LEW87022	1,090	0,014	CM2	2.3	Garenne et al., 2016	*
LEW90500	0,990	0,005	CM2	2.3	Garenne et al., 2016	*
MAC88100 ¹	0,894	0,010	CM2 Heated	2.3	Potin et al., 2020	*
MET01070	1,274	0,000	CM1	2.0	Garenne et al., 2016	*
MET01070 ¹	1,274	0,000	CM1	2.0	Potin et al., 2020	*
Mighei (*) ¹	0,994	0,003	CM2	2.3	Poggiali personal comunicati	*

					on	
MIL07700	0,570	0,016	CM2 Heated	/	Garenne et al., 2016	*
MIL07700 ¹	0,570	0,016	CM2 Heated	/	Potin et al., 2020	*
MIL07700 ¹	0,570	0,016	CM2 Heated	/	Takir et al., 2013	*
Murchison ¹	0,956	0,002	CM2	2.4	Potin et al., 2020	*
Murchison ¹	0,956	0,002	CM2	2.4	Takir et al., 2019	*
Orgueil BM ¹	1,366	0,015	CI1	/	Potin et al., 2020	*
Orgueil BM ¹	1,366	0,015	CI1	/	Takir et al., 2019	*
Orgueil Smith. ¹	1,346	0,019	CI1	/	Potin et al., 2020	*
Orgueil Smith. ¹	1,346	0,019	CI1	/	Takir et al., 2019	*
QUE97990 ¹	0,959	0,000	CM2	2.5	Potin et al., 2020	*
QUE97990 ¹	0,959	0,000	CM2	2.5	Takir et al., 2013	*
Tagish Lake lithology 4 ¹	0,642	0,000	C2	/	Potin et al., 2020	***
Tagish Lake ¹	0,720	0,003	C2	/	Takir et al., 2019	*
Tagish Lake ¹	0,717	0,004	C2	/	Takir et al., 2019	*
WIS91600	0,878	0,000	CM2 Heated	/	Garenne et al., 2016	**
WIS91600 ¹	0,878	0,000	CM2 Heated	/	Potin et al., 2020	**

1022