



Publication Year	2019
Acceptance in OA	2020-07-21T10:12:21Z
Title	Mineralogical analysis of quadrangle Ac-H-10 Rongo on the dwarf planet Ceres
Authors	ZAMBON, Francesca, CARROZZO, FILIPPO GIACOMO, TOSI, Federico, CIARNIELLO, Mauro Combe, J. Ph., FRIGERI, ALESSANDRO, DE SANCTIS, MARIA CRISTINA, Thangjam, G., Nathues, A., Hoffmann, M., LONGOBARDO, ANDREA, Stephan, K., RAPONI, Andrea, Ammannito, E., Krohn, K., McFadden, L. A., PALOMBA, Ernesto, Raymond, C. A., Russell, C. T., Dawn Science Team
Publisher's version (DOI)	10.1016/j.icarus.2017.09.021
Handle	http://hdl.handle.net/20.500.12386/26546
Journal	ICARUS
Volume	318

Mineralogical Analysis of the Quadrangle Ac-H-10 Rongo on Dwarf Planet Ceres

F. Zambon^{a,*}, F. G. Carrozzo^a, F. Tosi^a, M. Ciarniello^a, J. Ph. Combe^b, A. Frigeri^a, M.C. De Sanctis^a, G. Thangjam^c, A. Nathues^c, M. Hoffmann^c, A. Longobardo^a, K. Stephan^d, A. Raponi^a, E. Ammannito^e, K. Krohn^d, L.A. McFadden^f, E. Palomba^a, C.A. Raymond^g, C.T. Russell^h, and the *Dawn* Science Team

^a INAF-IAPS Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere, 100, I-00133 Rome, Italy;

^b Bear Fight Institute, 22, Fiddler's Road, P.O. Box 667, Winthrop, WA, 98862, USA;

^c Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, D-37077 Göttingen, Germany;

^d Institute of Planetary Research, German Aerospace Center (DLR), Rutherfordstrasse 2, D-12489 Berlin, Germany;

^e Italian Space Agency (ASI), Via del Politecnico snc, I-00133 Rome, Italy;

^f NASA/Goddard Space Flight Center, Greenbelt, 8800 Greenbelt Road, MD 20771, USA;

^g NASA/Jet Propulsion Laboratory and California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA;

^h Institute of Geophysics and Planetary Physics, University of California at Los Angeles, 3845 Slichter Hall, 603 Charles E. Young Drive, East, Los Angeles, CA 90095-1567, USA.

Proposed Running Head: Mineralogical Analysis of the Quadrangle Ac-H-10 Rongo on Dwarf Planet Ceres

*** Corresponding author:** Dr. Francesca Zambon
INAF-IAPS Istituto di Astrofisica e Planetologia Spaziali
Via del Fosso del Cavaliere, 100, I-00133 Rome, Italy
Phone: +39-06-45488-760
Email: francesca.zambon@iaps.inaf.it

Version 3.0 (30 April 2017)

To be submitted to:

Icarus

**Special issue on the mineralogical mapping of the Ceres quads
(T.B. McCord, F. Zambon, guest editors)**

40

41 **Abstract**

42 Quadrangle Ac-H-10 ‘Rongo’ (22°S-22°N, 288°E-360°E) shows a fairly homogeneous topography,
43 with the presence of some elevations such as *Ahuna Mons*, *Liberalia Mons*, and *Samhain Catenae*. The
44 southern region of the quadrangle is characterized by a lower elevation associated with Urvara and
45 Yalode craters. A substantial variability in the 2.7- μ m band depth distribution is observed across the
46 Rongo quadrangle, indicating an east-west gradient in the abundance of Mg-phyllsilicates. The NH₄-
47 phyllsilicates distribution appears quite homogeneous except for some localized regions, such as
48 crater Haulani’s ejecta, the flanks of Ahuna Mons and crater Begbalel. The two band depths at 2.7 and
49 3.1 μ m display an overall low correlation, suggesting a variable degree of mixing between Mg-
50 phyllsilicates and NH₄-phyllsilicates. At the local scale, mineralogical phases other than
51 phyllsilicates are observed. Quadrangle Rongo includes sodium carbonate-rich regions, such as the
52 flanks of Ahuna Mons, a localized area in Liberalia Mons and crater Begbalel, which often display a
53 reduction in both the 2.7- and 3.1- μ m band depths, associated with an increased band depth at $\sim$ 4 μ m,
54 related to the presence of Na-rich carbonate phases. This suggests recent hydrothermal activity in this
55 area, due to several episodes of cryovolcanism, or impacts that unveiled a peculiar composition in the
56 shallow subsurface. Alternatively, the crust in this region might show a variable degree of
57 compactness, such that the formation of Na-carbonates is favored only in specific locations (De Sanctis
58 et al., 2016; Ruesch et al., 2016; Zambon et al., 2017). From a geological standpoint, quadrangle Ac-H-
59 10 Rongo shows a correlation between its two main geologic units (Platz et al., 2017) and the
60 distribution of Mg-phyllsilicates, suggesting a link between geology and mineralogy in this area.

61

62

63 **1. Introduction**

64 The NASA Dawn mission entered orbit around the dwarf planet Ceres, the largest and most massive
65 object in the main asteroid belt, on 6 March 2015 (Russell et al., 2016). Dawn is equipped with three
66 instruments: the Framing Camera (FC), the Visible and InfraRed Spectrometer (VIR), and the Gamma
67 Ray and Neutron Detector (GRaND) (Sierks et al., 2011; De Sanctis et al., 2011; Prettyman et al.,
68 2011). The broad coverage and variable resolution of the data acquired by Dawn's payload during the
69 overall orbital phase allowed for deciphering the geology, surface composition, mineralogy and internal
70 structure of this intriguing body.

71 Prior to Dawn, several ground-based observations revealed the presence of an absorption band at ~ 3
72 μm . This feature was interpreted as due to structural OH groups and adsorbed or interlayer H_2O
73 molecules in clay minerals, inferring that the dominant minerals on the surface of Ceres were hydrated
74 clay minerals structurally similar to terrestrial montmorillonite (Lebofsky, 1978; Lebofsky et al., 1981).
75 Larson et al. (1979) suggested that the surface of Ceres was compatible with mixtures of opaque
76 materials and hydrated silicates. Other authors suggested that the $3.07 \mu\text{m}$ band could be due to
77 ammoniated phyllosilicates, specifically ammonium-bearing saponite (King et al., 1992) or hydrated
78 smectite clays (Feierberg et al., 1981). Rivkin et al. (2006) associated the extra absorption near the 3 -
79 μm band to Fe-rich cronstedrite and carbonates. The presence of phyllosilicates and carbonate
80 compounds was confirmed by observations carried out with the Keck II telescope (Carry et al., 2008).

81 Hyperspectral images acquired by VIR at spatial resolution ranging between ~ 0.10 and $\sim 1.1 \text{ km/pixel}$
82 shed light on Ceres' surface mineralogy. FC data enabled a thorough geologic mapping of the surface,
83 along with high-resolution color mapping complementary to VIR data, and topographic
84 characterization. VIR covers the overall wavelength range between 0.25 and $5.1 \mu\text{m}$ (De Sanctis et al.
85 2011), with the goal of identifying the diagnostic signatures of minerals present in its field of view. The

thermally corrected average spectrum of Ceres as observed by VIR (Raponi et al., 2017, this issue), reveals the presence of several absorption bands in the spectral range 2.6-4.0 μm (De Sanctis et al., 2015). These spectral signatures are located at 2.72-2.73 μm , 3.05-3.1 μm , 3.3-3.4 μm , and 3.95 μm (ibid). The prominent 2.72-2.73- μm band is diagnostic of hydrous minerals, more specifically Mg-phyllsilicates, the 3.05-3.1- μm band is associated with NH_4 -phyllsilicates, and the 3.3-3.4 μm band, which may be typical of organic compounds (Clark 1999, De Sanctis et al., 2017), can also be diagnostic of carbonates when observed in conjunction with the 4 μm band (Milliken and Rivkin, 2009). Hereafter, for simplicity we will refer to the band centered at 2.72 μm as the 2.7 μm band, the band centered at 3.05-3.1 μm band as the 3.1 μm band, the 3.3-3.5 μm band as the 3.4 μm band, and the 3.95 μm band as the 4 μm band. The application of a linear spectral unmixing model to telescopic spectra of Ceres yielded a best fit by using, as spectral end-members, Mg-bearing carbonates such as dolomite, calcite, and brucite (Milliken and Rivkin, 2009). Results of the nonlinear, spectral unmixing model based on the Hapke theory (Hapke, 1981, 1993) indicate that this average spectrum fits quite well with a mixture of NH_4 -montmorillonite or NH_4 -annite, antigorite, Mg-carbonate, and a spectrally featureless dark component (De Sanctis et al., 2015). On the other hand, spectral mixtures using brucite do not provide good fits. The first spatially resolved map of Ceres obtained on the basis of Dawn optical imagery (Nathues et al., 2015) revealed an overall dark surface (albedo 0.11) (Li et al., 2016) with widespread albedo variations, about 100 high-albedo spots (Palomba et al., 2017, submitted), and the presence of peculiar geological features seen at the local scale (0.01-1km).

Like for Vesta, Ceres' surface has been divided into fifteen quadrangles, which were later named for their respective individual features (Roatsch et al., 2016) (Fig. 1). For each quadrangle, both geologic maps (Williams et al., 2017) and mineralogical maps (Frigeri et al., 2017, this special issue) have been produced. In this paper, similar to what was previously done for the Av-13 Tuccia and Av-14 Urbinia quadrangles on Vesta (Zambon et al., 2015), we discuss the spectral characteristics of the quadrangle

110 Ac-H-10 Rongo, which is one out of five covering the equatorial region (Lon 288°-360°E, Lat 22°S-
111 22°N) (Fig. 1), bordering Yalode quadrangle in the south (Ammannito et al., 2017, this issue), Occator
112 quadrangle in the western side (Longobardo et al., 2017, this issue), Haulani in the eastern side (Tosi
113 et al., 2017, this issue) and Fejokoo quadrangle (Singh et al., 2017, this issue) in the northern side.

114

115 **2. Data**

116 The orbital mission at Ceres was divided in a number of phases: Survey, High-Altitude Mapping Orbit
117 (HAMO), Low-Altitude Mapping Orbit (LAMO), Extended Low-Altitude Mapping Orbit (E-LAMO),
118 Extended Juling Orbit (E-JO), and Extended Grand Orbit (E-GO). Each phase had a different length
119 and was carried out from a different altitude, with spatial resolution depending on the altitude over the
120 mean surface. In general, the altitude decreased from the Survey to LAMO, and then increased again
121 from the E-LAMO to E-JO and even more from E-JO to E-GO. As a result, in the Survey orbit phase
122 the average pixel resolution was ~1.10 km for VIR and ~0.41 km for FC; from the HAMO orbit it was
123 ~0.38 km for VIR and ~0.14 km for FC; in the LAMO and E-LAMO phases it was ~0.095 km for VIR
124 and ~0.035 km for FC; in the E-JO phase it was ~0.38 for VIR and ~0.14 km for FC (very similar to
125 the resolution achieved in the previous HAMO phase), while in the E-GO phase the spatial resolution
126 of VIR data was relatively coarse, i.e. 1.9-2.0 km/px, and hyperspectral images were acquired only in
127 the spectral subset 0.25-1.0 μm . The most limited spatial coverage and lowest signal-to-noise ratio
128 (SNR) were obtained in LAMO/E-LAMO, which make VIR data acquired in this period less optimal
129 for use and interpretation on a region as broad as an entire quadrangle of Ceres.

130 The maps shown in this paper were obtained by using VIR data acquired in the Survey and HAMO
131 mission phases, and FC data acquired in HAMO. Prior to mapping, all VIR spectra underwent a series
132 of processings. The data calibration follows the procedure described by Filacchione and Ammannito
133 (2014). Calibrated data were then treated so as to remove instrumental artifacts (Carrozzo et al., 2016)

134 and to remove the thermal emission, which shows up in spectra acquired on the dayside of Ceres at
135 wavelengths longward of $\sim 3.1 \mu\text{m}$ (Raponi et al. 2017, this issue). A photometric correction based on
136 the Hapke model (Hapke, 1981, 1993; Ciarniello et al., 2017) was applied to thermally corrected data,
137 to normalize to standard observation geometry (solar phase angle $\alpha = 30^\circ$, solar incidence angle $i = 30^\circ$,
138 and emission angle $e = 0^\circ$). Finally, at the end of this post-processing pipeline, global maps of several
139 spectral indices were produced (see Frigeri et al., 2017, this issue).

140 To complement our analysis, we include also some relevant maps derived by FC data during the
141 HAMO phase. FC has a spatial resolution ~ 2.67 times better than VIR (Sierks et al. 2011) and obtained
142 a broader coverage than VIR in the HAMO and LAMO/E-LAMO mission stages. FC is equipped with
143 7 narrow-band filters centered at different wavelengths in the overall spectral range $\sim 0.4\text{--}1.0 \mu\text{m}$ for
144 compositional analysis, and a broadband clear filter meant for geologic analysis (Sierks et al. 2011). In
145 all maps, including the spectral maps described in the previous subsection, longitudes are given in the
146 Ceres coordinate system (Raymond and Roatsch, 2015). A small crater ($\sim 0.4 \text{ km}$ diameter) named Kait,
147 located in this quadrangle, was chosen by the Dawn Team to define the prime meridian (Roatsch et al.,
148 2016). The location of this small crater is within the envelope of the broad feature identified in Hubble
149 Space Telescope (HST) data to which the previous system (Archinal et al., 2011) was anchored.

150

151 **3. Tools and techniques**

152 To carry out our mineralogical analysis based on VIR data, we selected the most relevant spectral
153 parameters, i.e. those showing the larger variability. In the following subsections we briefly describe
154 these parameters (see Frigeri et al. 2017, this issue, for more details).

155

156 *3.1 Framing camera maps*

157 FC data provide a high-resolution context that is useful to complement our mineralogical analysis of

158 Ceres. In this regard, we selected several FC-derived mosaics: a reflectance mosaic obtained in the
159 clear filter (map scale ~ 140 m/pixel) (Fig. 2A), a mosaic of spectral slope calculated between 0.555 and
160 0.829 μm (Fig. 2B), a digital terrain model at a scale of 60 pixels/degree (Fig. 2C), a RGB ‘enhanced’
161 color composite mosaic from FC colors: R : 0.96 μm ; G : 0.75 μm ; B : 0.44 μm (Fig. 2D), a RGB
162 ‘Clementine’ composite mosaic made from FC color ratios: R : 0.75/0.44 μm , G : 0.75/0.92 μm , B :
163 0.44/0.75 μm (Fig. 2E), and finally a geologic map that allows us to associate geologic and
164 mineralogical units (Fig. 2F).

165 The ‘Clementine’ color composite map (Pieters et al., 1994) is of interest to evaluate local spectral
166 variations at high spatial resolution, which may trace variations in composition. Comparing Clementine
167 color data and VIR spectral maps is indeed a powerful way to highlight possible correlations between
168 mineralogy and spectrally distinct structures seen in color imagery with higher spatial resolution. On
169 the other hand, while the Clementine color code proved to be optimal for lunar and Vesta data, it may
170 not necessarily be the best presentation to trace compositional differences in other rocky bodies of the
171 Solar System. Therefore, to explore the Rongo region we also use a FC enhanced color scheme, to
172 investigate the existence of spectral textures that would otherwise remain elusive or hidden.

173

174 *3.2 VIR maps*

175 *3.2.1 Albedo maps at 1.2 μm and 1.9 μm*

176 The maps shown in Fig. 3 display the albedo obtained by VIR data at two different wavelengths, 1.9
177 μm (Fig. 3A) and 2.1 μm (Fig. 3B). These wavelengths were chosen so as to avoid spectral regions
178 known or expected to host diagnostic signatures, and are therefore optimal to sample the spectral
179 continuum. As anticipated in Section 2, the albedo was calculated by applying a Hapke photometric
180 correction to the entire dataset (Ciarniello et al., 2017).

181

182 3.2.2. *Infrared spectral slopes*

183 The spectral slope (Fig. 4) is a useful parameter to investigate surface properties. Spectral slope
184 variations are associated with terrain's maturity and also provide complementary information on the
185 grain size (Clark 1999, Stephan et al., 2017). Lower spectral slope are often associated with young
186 terrains, higher spectral slope values are typical of older terrains (e.g. Nettles et al., 2011, Stephan et
187 al., 2017). Similar to albedo maps computed at 1.2 and 1.9 μm , spectral slope maps were also
188 computed in two distinct regions of the infrared spectrum where no absorption features show up. In
189 particular, we selected two spectral slopes between 1.891-1.163 μm (SI) and 2.250-1.891 (SII). The
190 method used to calculate this parameter is shown in Filacchione et al. 2012, and Frigeri et al. (2017,
191 this issue), describes it in detail.

192

193 3.2.3. *2.7 and 3.1 μm band depths*

194 The average reflectance spectrum of Ceres displays a number of absorption bands (De Sanctis et al.,
195 2015). Here we map the depths of the two bands centered at $\sim 2.7 \mu\text{m}$ and $\sim 3.1 \mu\text{m}$ (Fig. 5). These
196 bands are associated with magnesium phyllosilicates and ammoniated phyllosilicates, respectively (De
197 Sanctis et al., 2015, Ammannito et al., 2016). The depth of a band gives information about the
198 abundance of the absorbing minerals, but could be also affected by the presence of opaque materials,
199 and the grain size (Clark 1999). Band depth maps are calculated after applying Hapke photometric
200 correction (Ciarniello et al. 2017). For a more detailed description, we refer to Frigeri et al., 2017.

201

202 **4. Description of the quadrangles**

203 Quadrangle Ac-H-10 Rongo is characterized by numerous impact craters in the broad diameter range
204 $<100 \text{ m}$ to 205 km and variable states of preservation-from fresh to highly degraded. A number of
205 gently rising and partially coalesced landforms are observed across the quadrangle (Platz et al., 2017).

206 The FC-derived reflectance map obtained in HAMO (Fig. 2A) reveals the presence of several features:
207 *Ahuna Mons* (Lat 10.48°S, Lon 316.2°E, diameter ~20km) and *Liberalia Mons* (Lat 6.2°N, Lon
208 311.01°E, diameter ~90 km), *Samhain* and *Uhola* catenae in the western part of the quadrangle, and
209 several impact craters. Those with an official designation by the IAU and diameters in the range 40-100
210 km are: *Begbalel* (Lat 17.7°N, Lon 325.35°E, diameter ~102 km), *Rongo* (Lat 21.3°N, Lon 348.71°E,
211 diameter 68 km), with several crater wall collapse events as evidenced by the pronounced scalloped rim
212 (Platz et al., 2017), which gives the name to the quadrangle, and *Hatipowa* (Lat 16.8°S, Lon 357.71°E,
213 diameter 40 km). The maximum topographic relief across the quadrangle is ~11.1 km (Fig. 2C) (Platz
214 et al., 2017). The main feature of this quadrangle, Ahuna Mons, with a local radius of 485 km (19.4 km
215 × 13.8 km, and a maximum height of ~5 km on its steepest side), is the highest elevation in this
216 quadrangle and the highest mountain on Ceres (ibid.). Ahuna Mons' flanks are smooth and are
217 composed of bright material, primarily salts and carbonates (Ruesch et al., 2016, Zambon et al., 2017a).
218 The contact to the surrounding cratered terrain is sharp and only gradational where flank-induced flow
219 deposition occurred. The summit region exhibits linear to arcuate ridges with no preferred orientation
220 (Platz et al., 2017). Other elevations in this quadrangle are Liberalia Mons, Kait crater's area, and
221 Samhain Catenae. Conversely, the deepest topography is observed in the southern part of the
222 quadrangle (local radius 417 km), in Yalode basins (Ammannito et al., 2017, this issue).
223 The geologic map (Fig. 2F) highlighted two broad geological units: the most widespread is cratered
224 terrain, which covers large part of the quadrangle and more generally is the dominant surface unit on
225 Ceres, and Yalode ejecta material in the southwestern part of the quadrangle. With respect to these two
226 broad units, younger geologic units are found at the local scale: tholus material matching Ahuna and
227 Liberalia Mons, bright crater material in Begbalel, Liberalia Mons and other two features in the north-
228 eastern part of the quadrangle (Fig. 2F). Hummocky crater floor material is present inside many craters,
229 such as Begbalel, Rongo and Hitipowa. Haulani crater's ejecta, coming from the nearby Ac-H-6

230 Haulani quadrangle, have been identified as a separate, crater ray material unit. Individual ejecta rays
231 can be traced for up to 450 km (Platz et al., 2017). The southwestern part of the quadrangle, including
232 Samhain and Uhola catenae, is dominated by rough-textured material interpreted to represent ejecta
233 from Yalode Crater (260 km in diameter). Yalode ejecta material is often dissected and is clearly
234 distinct in texture from the cratered terrain. Detailed analysis of crater size-frequency distributions
235 revealed model ages, for the two main geological units, of about 540 Ma Yalode crater and about 1.8
236 Ga as formation age for the cratered terrain. Cratered terrain exhibits large variations in crater densities
237 across the globe (Hiesinger et al., 2016) with resulting model ages ranging between 1.4-3.4 Ga
238 (Pasckert et al., 2017, Williams et al., 2017, see also Platz et al., 2017).

239

240 **5. Global mineralogy of Ac-H-10 Rongo**

241 The enhanced color composite mosaic (red: 0.96 μm ; green: 0.75 μm ; blue: 0.44 μm) (Fig. 2D)
242 highlights that most of the surface in quadrangle Ac-H-10 (and more generally on Ceres) displays a
243 brownish background color, punctuated by other units characterized by different colors. Haulani
244 crater's ejecta, which dominate the eastern side of the quadrangle, is one the most prominent
245 multispectral unit, characterized by a striking bluish color (Tosi et al., 2017, this issue). Similar to
246 Haulani's ejecta, the flanks of Ahuna Mons and crater Begbalel are also characterized by a bluish color
247 shade. The same color dominates the western side of the quadrangle, bordering the Occator quadrangle
248 (Longobardo et al., this issue) in correspondence with Samhain Catenae, while Liberalia Mons is stands
249 out for its albedo (0.037 ± 0.002 at 1.2 μm , 0.039 ± 0.001 at 1.9 μm). In the Clementine color
250 presentation (red: 0.75/0.44 μm , green: 0.75/0.92 μm , blue: 0.44/0.75 μm), dark materials appear dark
251 bluish/violet, and bright materials are yellow-green, with intermediate albedo surfaces appearing cyan
252 (Fig. 2E). The Clementine composite map of quadrangle Ac-H-10 shows that most of the surface is
253 reddish, while Haulani craters' ejecta, the bright area in Liberalia Mons, crater Begbalel and the region

254 of Samhain Catenae (Fig. 2D) stand out in displaying an overall bluish/violet color. Ahuna Mons is the
255 only feature of this quadrangle showing a cyan color around the flanks. The map of spectral slope,
256 calculated between 0.555 and 0.829 μm (Fig. 2B), reveals that the majority of the quadrangle has a
257 greenish to whitish color, indicating a null (flat) or slightly positive slope value. Haulani ejecta stands
258 out for its magenta and violet colors corresponding to negative values of spectral slope (Stephan et al.,
259 2017). Along with Haulani ejecta, also the flanks of Ahuna Mons and Liberalia Mons are characterized
260 by negative spectral slopes. Extreme negative values (down to -0.148) are recorded in Ahuna Mons and
261 Liberalia Mons. On a broader scale within quadrangle Ac-H-10, the 0.555-0.829 μm spectral slope
262 does not show any particular trend. Age determination indicates that the bluish material seen in Figs,
263 2D and 2E is mainly associated with the youngest impact craters or cryovolcanic events on Ceres
264 (Nathues et al., 2016; Schmedemann et al., 2016). The spectral slope (SI and SII) maps derived by VIR
265 in the near infrared range, show similar results. SI covers a range of values between 0.05 and 0.14,
266 while SII spans from -0.03 and 0.07, with an average value of 0.095 ± 0.014 for SI, and 0.022 ± 0.015
267 for SII. The region showing the largest variability in terms of spectral slopes is the flanks of Ahuna
268 Mons, in which both SI and SII show the lowest values (slope I: 0.05, slope II -0.03) within the
269 quadrangle. Along with Ahuna flanks, Liberalia Mons and Haulani ejecta (Tosi et al., 2017, this issue)
270 also display low infrared spectral slope values. The rest of the quadrangle is characterized by flat or
271 slightly positive spectral slope values. The blue slope is generally a proxy for younger, less processed
272 material. This implies that Ahuna Mons and Haulani's ejecta are also the youngest features on Ceres
273 (Ruesch et al. 2016; Stephan et al 2017; Schroeder et al, 2017).

274 From the FC-derived clear filter reflectance mosaic (Fig. 2A), whose reflectance values range from
275 0.01 to 0.06, one can infer the existence of bright and dark materials, which stand out as having
276 substantially higher or lower reflectances than the quadrangle's average value of 0.03.

277 Albedo maps retrieved in the near infrared on the basis of VIR data (Fig. 3) at 1.2 and 1.9 μm show a

278 fairly homogeneous trend with an average albedo of 0.034 ± 0.001 at $1.2 \mu\text{m}$ and 0.036 ± 0.001 at 1.9
279 μm . Nevertheless, some regions, such as the flanks of Ahuna Mons (0.038 ± 0.001) (Ruesch et al.,
280 2016; Zambon et al. 2017), and a localized area in Liberalia Mons (0.037 ± 0.002 at $1.2 \mu\text{m}$, $0.039 \pm$
281 0.001 at $1.9 \mu\text{m}$), appear brighter than the average, while Haulani's ejecta are darker (0.0335 ± 0.0006 at
282 $1.2 \mu\text{m}$ and 0.0356 ± 0.0006 at $1.9 \mu\text{m}$) (Stephan et al., 2017; Krohn et al., 2017; Tosi et al., 2017, this
283 issue), as much as Ahuna Mons' top (0.0313 ± 0.0008 at $1.2 \mu\text{m}$ and 0.0331 ± 0.0008 at $1.9 \mu\text{m}$). The
284 analysis of the strongest bands of Ceres spectra, those at $2.7 \mu\text{m}$ and $3.1 \mu\text{m}$ interpreted as due to Mg-
285 and NH_4 -rich phyllosilicates, do not emphasize any band center variation, implying no relevant
286 compositional changes. Conversely, band depth maps (Fig. 5) reveal a regional variability within the
287 quadrangle. $2.7 \mu\text{m}$ band depth values span between 0.186 and 0.212, while the band depth at $3.1 \mu\text{m}$
288 ranges between 0.07 and 0.1. The eastern region of the Rongo quadrangle is depleted in Mg-
289 phyllosilicates with respect to the western part (Fig 5A). The region between longitude 336° - 348°E and
290 latitude 22°S - 10°N in latitude presents the highest $2.7 \mu\text{m}$ band depth values within this quadrangle
291 (0.212), while the lowest values are registered in the Ahuna Mons flanks (0.186). The $3.1 \mu\text{m}$ band
292 depth (Fig. 5B) shows a homogeneous distribution, with a lower amount of NH_4 -phyllosilicates, mostly
293 corresponding to the flanks of Ahuna Mons flanks and Haulani's ejecta, but also in the region of
294 Samhain catenae and crater Bagbalel.

295 In Fig. 6, we show maps that correlate the $2.7 \mu\text{m}$ band with the $3.1 \mu\text{m}$ band. Red-green-blue color
296 composites are commonly used to represent three different datasets; however the drawback is that it is
297 not possible to represent all the colors of the map in a single color table (a real one would have three
298 dimensions), which limits the accuracy and relevance of the interpretations. It is however possible to
299 represent two parameters using two-dimensional color tables based on mixtures of four or more colors
300 (e.g. Combe et al., 2015; Combe et al., 2017, this issue). The interpretation of the colors can be eased
301 by displaying a two-dimensional scatterplot of the dataset at the same scale or as an overlay to the color

302 table. Fig. 6A is produced by combining FC albedo map and using VIR data with the following color
303 combination: red = 2.7 μm band depth, green = FC albedo at 0.45 μm , blue = 3.1 μm band depth. In
304 this color code, green areas have a high albedo, while redder areas have higher 2.7 μm band depth, and
305 bluer areas have higher 3.1 μm band depth. The areas where all three are present in high amount
306 appears white. In Fig. 6B, same global and Ac-H-10 quadrangle map is shown using a color scale
307 which emphasizes only extremes spectral composition. The colors represented in panel c have a direct
308 correspondence to the colors on the map (Fig. 6) (see Combe et al., 2017, this issue and Singh et al.,
309 2017, this issue).

310 The yellow region between Samhain catenae and Liberalia Mons (Fig. 6A) shows low average values
311 for both the band depths, while the regions in blue, which mostly mark the northern and the
312 southeastern region of the quadrangle, present the highest values for both the band depths. The yellow
313 region in the eastern region of the quadrangle corresponds to the Haulani's ejecta. However, the flanks
314 of Ahuna Mons display the minimum values for both the band depths. Ahuna Mons is a recent feature,
315 younger than the neighboring crater. The features showing the larger difference in terms of band depth
316 (Fig. 6B) are Ahuna Mons and Haulani ejecta.

317 The Rongo quadrangle is characterized by significant spectral variability on the basis of VIR-derived
318 spectral parameters and data, which in turn indicate substantial mineralogical variations. Ac-H-10 is
319 generally dominated by a widespread spectral unit, on which other smaller and younger units are
320 superimposed. For example, the geologic unit classified as Yalode ejecta material in the southeastern
321 region of the quadrangle seems to be characterized by lower values of the 2.7 μm band depth, while the
322 widespread unit named cratered terrain is characterized by the highest values of the 2.7 μm band depth.
323 The unit classified as tholus material, which includes both Ahuna Mons and Liberalia Mons, seems to
324 be characterized by higher albedo and medium-to-low values of the two band depths for Ahuna Mons,
325 while higher 3.1 μm band depths values are found for Liberalia Mons.

326 The smooth unit and the 17-km crater unit close to Ahuna have a similar age: 210 ± 30 Ma and $160 \pm$
327 30 Ma, respectively, using the Lunar Derived Model or 70 ± 20 Ma and 70 ± 20 Ma, respectively,
328 using the Asteroid Derived Model (Ruesch et al., 2016). Low spectral slope values confirm the younger
329 age of this structure. Ahuna Mons has been interpreted as an extrusion due to several episodes of
330 cryovolcanism. The composition of its flanks highlight Na-rich carbonate material coming from the
331 subsurface (Zambon et al., 2017).

332 The histogram in Fig. 7A, related to the frequency of the band depths at $2.7 \mu\text{m}$ and $3.1 \mu\text{m}$, shows that
333 $\sim 70\%$ of $3.1 \mu\text{m}$ band depth values within the quadrangle range between 0.08 and 0.9, while most 2.7
334 μm band depth values span around 0.19 and 0.21. Consistent with the average reflectance spectrum of
335 the surface of Ceres as measured by VIR, where the absorption centered at $2.72\text{-}2.73 \mu\text{m}$ is broader
336 than the absorption centered at $3.05\text{-}3.1 \mu\text{m}$ (De Sanctis et al., 2015), the $2.7\text{-}\mu\text{m}$ band depth is larger
337 than the $3.1 \mu\text{m}$ band depth, with most recurrent values in the range 0.188-0.212 (average value 0.199)
338 for $2.7 \mu\text{m}$ band depth and 0.069-0.1 (average value 0.084) for the $3.1 \mu\text{m}$ band. The $3.1 \mu\text{m}$
339 distributions have a narrow width, with balanced maximum values of frequency and comparable shapes
340 hardly modeled by a Gaussian fit, which overall demonstrates the goodness of photometric correction,
341 and at the same time testifies a relatively homogeneous distribution of the abundance of the featureless
342 spectral endmember across the entire quadrangle. However, the $2.7 \mu\text{m}$ band depth distribution is
343 narrower than the $3.1 \mu\text{m}$ distribution, indicating a higher degree of variability in the abundance of
344 ammoniated phyllosilicates across the quadrangle, as shown in Fig. 5B. For comparison, in other
345 nearby quadrangles of Ceres the observed statistics may show a slightly different distribution (e.g.,
346 Tosi et al., 2017, this issue). This aspect is also important to associate the values of 2.7 and $3.1 \mu\text{m}$
347 band depth that we observe to relative abundances of Mg-rich and NH_4 -rich phyllosilicates,
348 respectively.

349 The band depth value, which is indicative of a mineral's abundance, may also be affected by the
350 presence of opaque phases and by the grain size (Clark, 1999). In order to quantify abundance values, a
351 spectral unmixing model has to be applied to the observed spectral data, which is beyond the scope of
352 our work. However, from the spectral unmixing modeling carried out previously to establish the global
353 average mineralogy of Ceres, it turns out that best fits with respect to the average reflectance spectrum
354 of Ceres as measured by VIR are obtained by using antigorite with a grain size of 90 μm , Mg-
355 carbonates with a grain size of 10 μm , and a featureless dark component with a grain size of 80 μm (the
356 grain size for NH_4 -rich phyllosilicates could not be determined unequivocally) (Fig. 4a and Extended
357 Data Table 2 in De Sanctis et al., 2015). So, under the reasonable assumption that these grain size
358 values are recurrent on a broadly regional scale including quadrangle Ac-H-10, our 2.7 and 3.1 μm
359 band depth values may be associated to mineral abundances rather than to variations in the grain size
360 distribution.

361 The density scatterplot in Fig. 7B does not show any significant correlation between the two bands. The
362 linear model proves inadequate to describe the trend of the ratio of Mg-rich/ NH_4 -rich phyllosilicates: as
363 revealed by the chi-square, the distribution is essentially non-linear, and the average coefficient of
364 determination is low, meaning that a substantial correlation between these two variables is generally
365 not met throughout the quadrangle, but only for specific geologic features found at the local scale.

366 By mapping the value of the ratio between the measured 2.7 μm band depth and the 2.7 μm /3.1 μm
367 band depth linear approximation (Fig. 8), one can see that the northeastern part of the quadrangle, in
368 green, is the closest to the linear model, while the southwestern region presents lower values with
369 respect to the linear model and the blue region indicates an opposite behavior. Locations with 2.7 μm
370 band depth values significantly lower than the linear model displayed in Fig. 8, i.e. with a lower value
371 of the ratio Mg-rich/ NH_4 -rich phyllosilicates, generally correspond to the area of Ahuna Mons and
372 Yalode ejecta material. Conversely, values significantly higher than the linear model, i.e. with a higher

373 value of the ratio Mg-rich/NH₄-rich phyllosilicates, concentrate in the southeastern part of the
374 quadrangle.

375 Other than the 2.7 and 3.1 μm absorption bands, also other two prominent band at 3.3-3.5 μm and 3.94-
376 4.0 μm have been observed on the basis of VIR data (De Sanctis et al., 2015). When observed together,
377 the 3.4 μm band and the 4 μm bands are indicative of the presence of carbonates (De Sanctis et al.,
378 2015; Carrozzo et al., 2017, submitted). Conversely, the existence of the 3.4 μm band alone is
379 indicative of organic compounds, as recently discovered in the area of crater Ernutet in Ac-H-2
380 Coniraya quadrangle (Raponi et al., 2017, this issue) by De Sanctis et al. (2017).

381 Non-linear spectral unmixing based on the Hapke method indicates that the surface of Ceres is
382 characterized by an overall distribution of (Mg, Ca)-carbonates, with localized areas enriched in Na-
383 carbonates, such as crater Occator (De Sanctis et al., 2016), Azzaca area (Carrozzo et al., 2017, this
384 issue), crater Kupalo (De Sanctis et al., 2017, this issue) and the flanks of Ahuna Mons (Zambon et al.,
385 2016). As shown by Carrozzo et al. (2017, submitted), also Ac-H-10 Rongo includes more than one
386 Na-rich site: besides Ahuna Mons, Na-rich carbonates have been found in Liberalia Mons, in crater
387 Begbalel, and in crater Hatipowa. Na-rich carbonates are believed to be related to past hydrothermal
388 activity, brought out by impacts or cryovolcanism episodes.

389

390 **5. Discussion and Conclusion**

391 A thorough mineralogical analysis of the Ac-H-10 Rongo quadrangle, based on the interpretation of
392 several spectral parameters, indicates a variegated mineralogy. Rongo's topography includes high
393 elevations such as Ahuna Mons and Liberalia Mons, and depressed regions such as the area of craters
394 Urvara and Yalode and the region east of crater Begbalel. From a mineralogical standpoint, we can
395 identify different units. The parameters that show larger variability are the 2.7 and 3.1 μm band depths,
396 which highlight a trend in the distribution of the Mg-and and NH₄-phyllosilicates, respectively. The

band depth at 2.7 μm presents larger values in the eastern region of the quadrangle, matching the oldest geologic unit, i.e. cratered material. The southwestern region of the quadrangle, corresponding to Yalode ejecta material, is characterized by a depletion in OH-rich minerals, as much as the ejecta of crater Haulani. The band depth distribution at 3.1 μm appears more homogeneous, but a depletion in NH_4 -phyllosilicates is observed in Haulani's ejecta. In general, the two band depths are mostly uncorrelated.

The main tholus within quadrangle Ac-H-10 Rongo is Ahuna Mons, a young feature interpreted as extrusion due to multiple episodes of cryovolcanism (Ruesch et al., 2016). Ahuna Mons was formed by a volcanic process involving the ascent of cryomagma and extrusion onto the surface followed by dome development. The mons and tholus upon which it sits might have shared a common reservoir at depth (Ruesch et al., 2016). Their different morphologies might be related to a change in the rheological properties (e.g., chemistry and temperature) of the reservoir with time or during ascent (ibid.). This is confirmed by a generally greater abundance of Na-carbonates in Ahuna compared to the surroundings. Although the overall composition is not too dissimilar to what is found elsewhere on Ceres, at the local scale Ahuna Mons emerges to have a lower abundance of ammoniated and hydrous mineral phases, a reduction of the spectral slope both in the visible and in the infrared range, and a greater abundance of Na-rich carbonates than the surrounding areas observed at the same spatial resolution (Platz et al., 2017; Zambon et al., 2017). The presence of Na-carbonates has been interpreted as evidence of recent hydrothermal activity (De Sanctis et al., 2016) and is consistent with a cryovolcanic origin of Ahuna Mons, which would locally raise a portion of terrain by exposing fresh subsurface material richer in carbonates. Besides Ahuna Mons, also other region in Rongo quadrangle display Na-carbonates enrichments. A further ancient tholus located within crater Begbalel is also interpreted to be a cryovolcanic edifice by Platz et al. (2017), and also here Na-carbonates have been observed (Carrozzo et al., 2017). Also a third tholus, Liberalia Mons, displays Na-carbonates deposits, in correspondence

421 with a small bright crater on the top. Other tholi are also identified in quadrangle Ac-H-5 Fejokoo
422 (Singh et al., 2017, this issue). Haulani crater's ejecta material displaying a substantial negative spectral
423 slope is the product of material melted and vaporized during the impact event, which may have been
424 ejected to significant distances at high velocities (Stephan et al., 2017). The composition we observe
425 today in Haulani's ejecta may have been favored by both the pre-existing mineralogy and the
426 characteristics of the impact event. Space weathering, in terms of diurnal temperature variations and
427 micrometeoritic impacts forming a regolith layer of fine-grained phyllosilicate dust, may be responsible
428 for the fading of the blue color over time (Stephan et al., 2017). Ahuna Mons is among the bluest units
429 on Ceres, after crater Haulani and crater Oxo (Singh et al., 2017, this issue), which is indicative of a
430 younger age and less processed material.

431 In general, in correspondence with Na-carbonates enrichment, we observe an abundance reduction of
432 Mg- and NH₄-phyllosilicates. Na-carbonates are endogenous on Ceres and this material is typical of the
433 underlying layers of the surface, deposited after brine evaporation related to hydrothermal activities,
434 brought out by impact or episodes of cryovolcanism (De Sanctis et al., 2016, Ruesch et al., 2016).
435 Ceres surface is highly cratered (Williams et al., 2017), but Na-carbonates are present only in some
436 specific regions seen at the local scale, indicating a non-uniform distribution of this compound on
437 Ceres' shallow subsurface or alternatively a different compactness of the crust at different locations.
438 Furthermore, the depletion in Mg-phyllosilicates observed in specific regions could be related to the
439 energy of impact, which may have caused a loss of OH-rich minerals but not of NH₄-phyllosilicates,
440 explaining the overall non-correlation between this two bands' strength. Our analysis shows that
441 quadrangle Ac-H-10 Rongo has a variegated mineralogy, which is indicative of a recent past activity.
442 Furthermore, a link between the two main geological units and spectral variability is been observed.
443 Future work should focus on VIR data obtained in the main areas of Rongo quadrangle at the highest
444 available pixel resolution (i.e., ~0.10 km), applying spectral unmixing techniques (e.g., Zambon et al.,

445 2016; Tosi et al., 2015) able to quantify the abundances of a number of mineral species known or
446 expected to exist at the surface, including carbonates.

447

448 **Acknowledgments**

449 We thank the Italian Space Agency (ASI) and NASA for supporting this work. The VIR instrument
450 was funded and coordinated by the ASI and built by Selex ES, with the scientific leadership of the
451 Institute for Space Astrophysics and Planetology, Italian National Institute for Astrophysics, Italy. The
452 VIR is operated by the Institute for Space Astrophysics and Planetology, Rome, Italy. A portion of this
453 work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under
454 contract to NASA. Dawn data are archived in NASA's Planetary Data System; VIR spectral data may
455 be obtained at <https://sbn.psi.edu/pds/resource/dwncvir.html>

456

457 **Figure captions**

458 **Figure 1:** Index map of the fifteen quadrangles that are defined for the surface of Ceres (Roatsch et al.,
459 2016). The quadrangle images are made using HAMO Framing Camera clear filter images of Ceres,
460 obtained by the Framing Camera team at the Max Planck Institute and German Aerospace Center
461 (DLR). Red rectangle indicates the quadrangle Ac-H-10 Rongo, located at 288°- 360°E, 22°S - 22°N.

462 **Figure 2:** Maps of Ac-H-10 Rongo quadrangle retrieved by the Framing Camera (FC) data relative to
463 the HAMO phase of the mission (spatial resolution ~ 140 m/px). **A:** Reflectance map of Ac-H-10
464 Rongo, obtained through photometric correction of FC clear-filter data acquired in the HAMO mission
465 phase. Surface features that have received an official designation by the IAU are marked in yellow
466 color. **B:** RGB composite of the Ac-H-10 Rongo quadrangle showing spectral slope calculated between
467 0.555 and 0.829 μm . **C:** Topography/elevation map of Rongo quadrangle derived using HAMO DTM
468 (Preusker et al., 2016), at a scale of 60 pixels/degree. The rainbow color palette follows topography
469 (local radius), with the highest elevations in red and the lowest terrains in dark blue/violet.
470 **D:** RGB composite of the Ac-H-10 Rongo quadrangle made from FC colors: $R: 0.96 \mu\text{m}$; $G: 0.75 \mu\text{m}$;
471 $B: 0.44 \mu\text{m}$ ('enhanced' color composite). Compared to the Clementine presentation, this color scheme
472 enhances differences in albedo. **E:** RGB composite of the Ac-H-10 Rongo quadrangle made from FC
473 color ratios: $R: 0.75/0.43 \mu\text{m}$, $G: 0.75/0.92 \mu\text{m}$, $B: 0.43/0.75 \mu\text{m}$ ('Clementine' color composite). Color
474 ratios may enhance differences in material and composition. **F:** Geologic map of Ac-H-10 Rongo,
475 adapted from Platz et al. (2017). The broad brownish geologic unit is mapped as 'cratered terrain' (*crt*),
476 while the pink color indicates 'Yalode ejecta' (*Ye*). Red patches of 'tholus material' (*th*) are found in
477 the correspondence with Ahuna Mons and in the vicinity of Begbalel crater. Light yellow patches are
478 'crater bright material' (*cb*), while yellow patch represent 'crater material' (*c*). Light pink and dark
479 green indicate 'crater floor material hummocky' (*cfh*) and 'talus material' (*ta*), respectively.

480 **Figure 3:** **A:** Reflectance map of Ac-H-10 Rongo, obtained through photometric correction of VIR
481 data acquired at 1.2 μm in the Survey and HAMO mission phases, interpolated on a grid with a fixed
482 resolution of ~ 140 m/pixel, photometrically corrected by using the method described by Ciarniello et
483 al. (2017), i.e. a Hapke photometric correction to standard observation geometry ($i=30^\circ$, $e=0^\circ$, $\alpha=30^\circ$).
484 **B:** Reflectance map of Ac-H-10 Rongo, obtained through photometric correction of VIR data acquired
485 at 1.9 μm in the Survey and HAMO mission phases, interpolated on a grid with a fixed resolution of
486 140 m/pixel. The same photometric correction of Panel A was applied.

487
488 **Figure 4:** Two spectral slopes, calculated in the near infrared range 1.163-1.891 μm (**A**) and 1.891-
489 2.250 μm (**B**) on the basis of VIR infrared data. These spectral slopes are essentially consistent with the
490 spectral slope obtained from FC data in the visual range 0.555-0.829 μm at higher spatial resolution
491 (Fig. 2B): i.e., it is confirmed that crater Haulani ejecta, Ahuna Mons flanks and a localized region in
492 Liberealia Mons generally corresponds to a neat reduction in spectral slopes.

493
494 **Figure 5:** Distribution of 2.7 μm band depth (**A**) and 3.1 μm band depth (**B**) values across the Rongo
495 quadrangle, derived from VIR data. These band depths are sensitive to the abundance of magnesium-
496 bearing phyllosilicates and ammoniated phyllosilicates, respectively, and to the presence of opaque
497 contaminants. The overall distribution spans from lower depth (dark blue to blue) to greater depth (red
498 to dark red). Ahuna Mons flanks and Haulani ejecta are associated with the spectrally distinct material
499 have shallower 2.7 and 3.1 μm band depth values.

500

Figure 6: **a:** 2D scatterplot of 2.7 μm band depth as a function of 3.1 μm band depth computed for the entire surface of Ceres. **b:** four-color key and legend for Panel c (this figure) and panel A and B. Materials depleted in both Mg-rich phyllosilicates and NH_4 -rich phyllosilicates appear in yellow-orange colors, while materials enriched in both Mg-rich phyllosilicates and NH_4 -rich phyllosilicates are displayed in blue. The green color marks materials with enhanced abundance of Mg-rich phyllosilicates and depletion of NH_4 -rich phyllosilicates, while the purple color highlights an opposite situation, i.e. materials depleted in Mg-rich phyllosilicates and a relatively high abundance of NH_4 -rich phyllosilicates. **c:** Same 2D scatterplot of (a) superimposed on the four-color scheme represented in (b). **A:** four-color map of correlation between 2.7 μm band depth and 3.1 μm band depth. In this map, all VIR pixels are represented by a color according to the scheme defined panel b. **B:** Same kind of map as (A), but in this case the four-color map is partially masked by the 2D-scatter plot from the global dataset represented in panel a. In this map, only the purest compositions are represented by colored pixels, while all the others are dark.

Figure 7: **A:** Histograms of 2.7 μm band depth and 3.1 μm band depth values measured across quadrangle Ac-H-10 (after photometric correction), displayed in dark gray and light gray colors, respectively. A Gaussian fit is superimposed in the light blue color. The most recurrent values are in the range 0.19-0.22 (average value 0.195) for 2.7 μm band depth and 0.08-0.09 (average value 0.085) for 3.1 μm band depth. **B:** Density scatterplot of 2.7- μm band depth as a function of 3.1- μm band depth computed for the quadrangle Ac-H-10. A linear fit model (white dashed line) is superimposed on the distribution. Most data concentrate around the average values. The cluster shows a large spread and a moderate-to-low correlation in the linear fit model

Figure 8: Ratio between the measured 2.7 μm band depth and the 2.7 μm band depth /3.1 μm band depth linear fit model. This map shows where the surface material departs from an ideally linear correlation between the abundance of the two major mineral species. Dark blue to blue colors mark locations that have shallower 2.7 μm band depth than the linear model, while red to dark red shades mark locations that have larger 2.7 μm band depth than the linear model. If 2.7 μm band depth was perfectly correlated with 3.1 μm band depth, this map would appear uniformly green.

533

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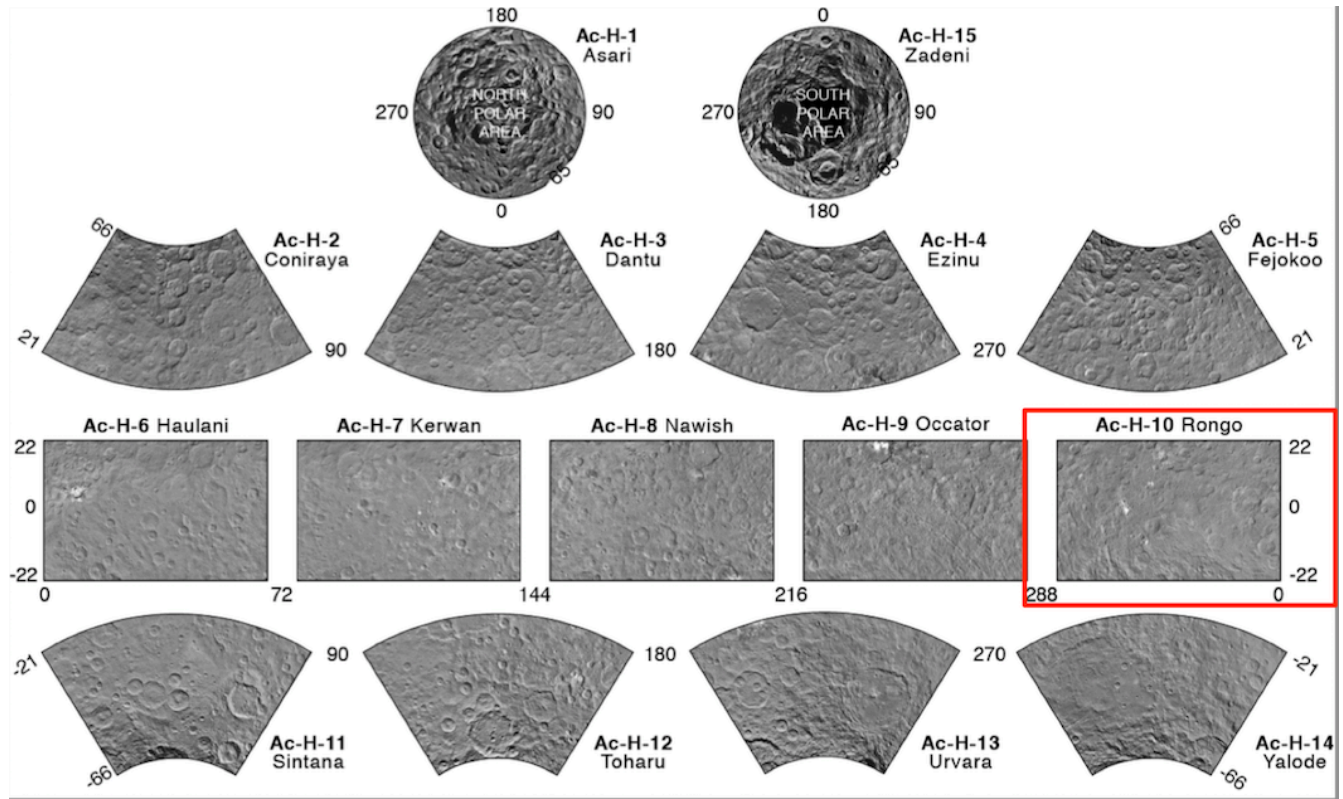
721 **Figures**

Figure 1

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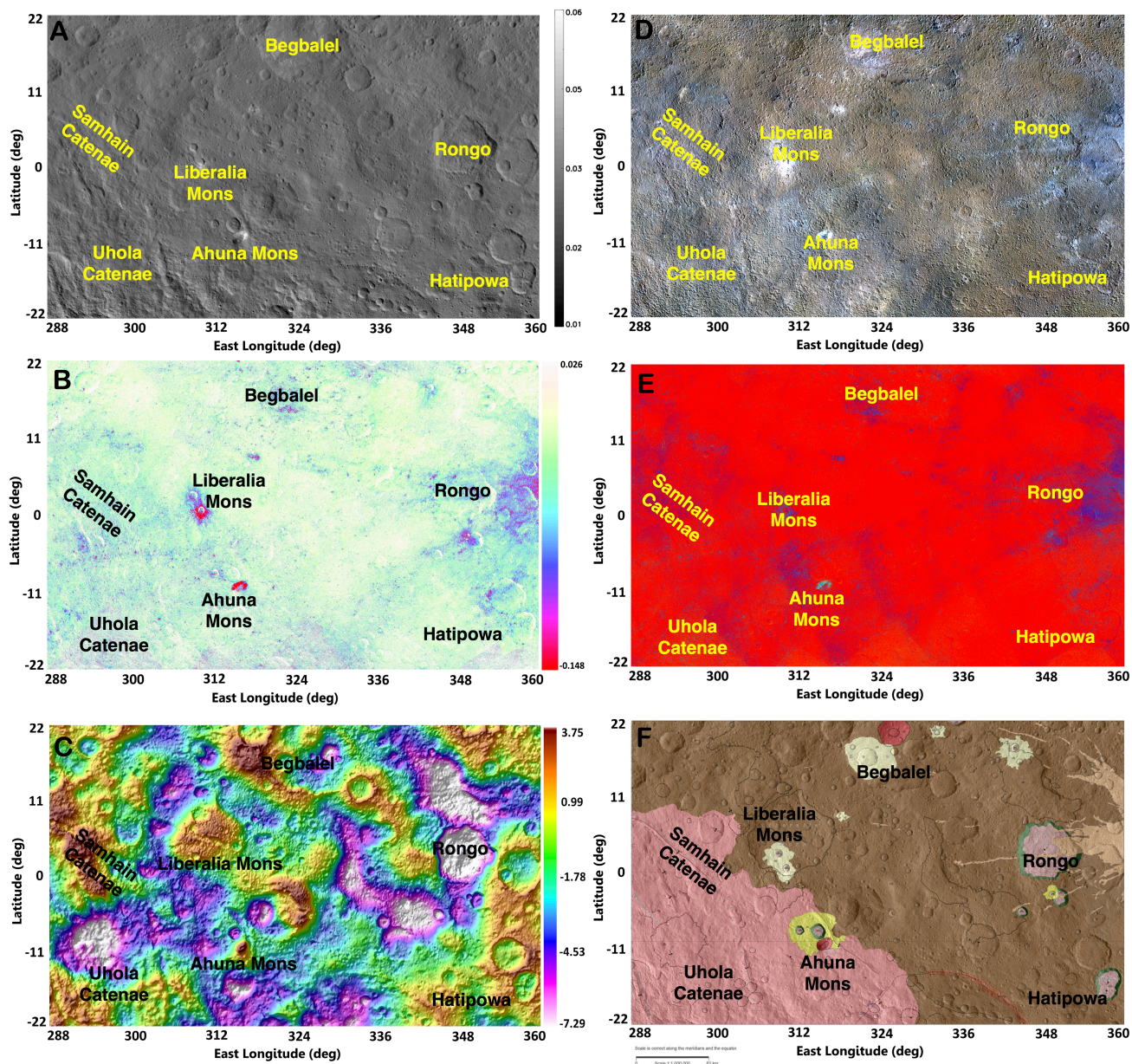


Figure 2

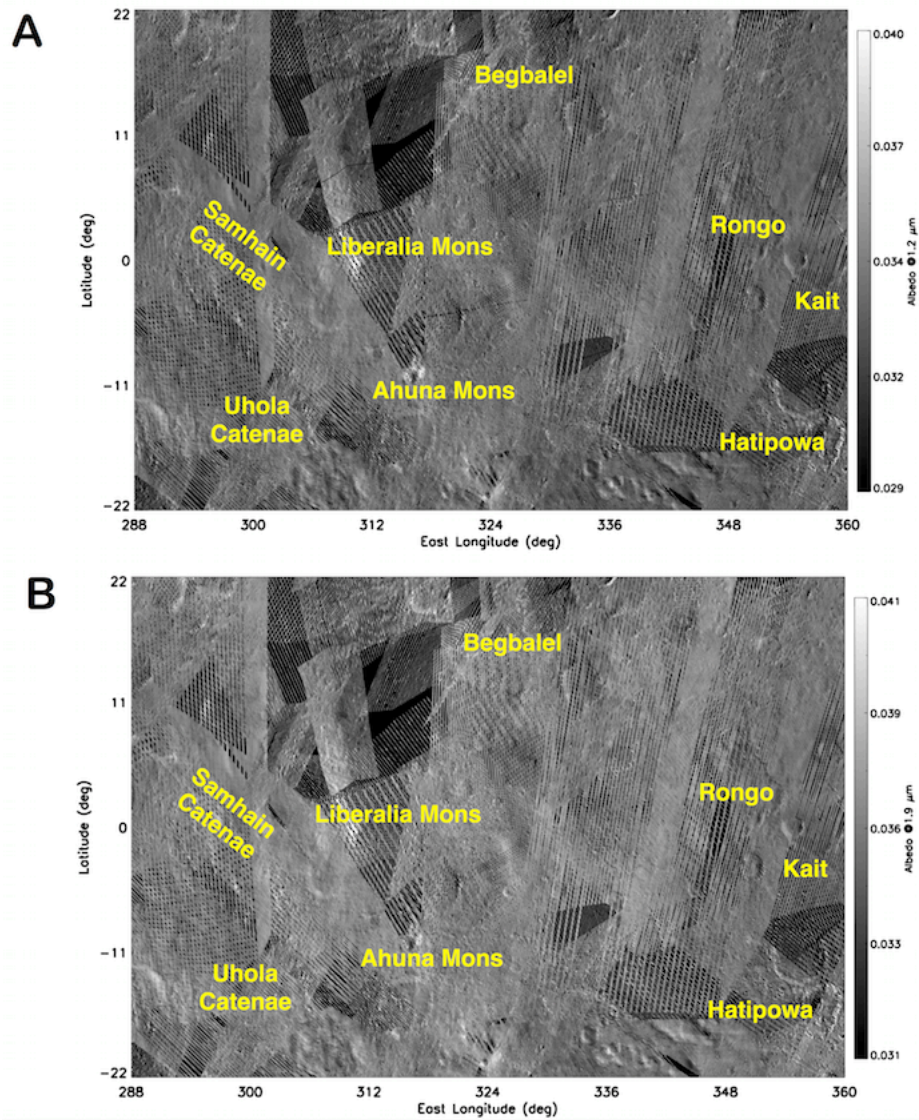


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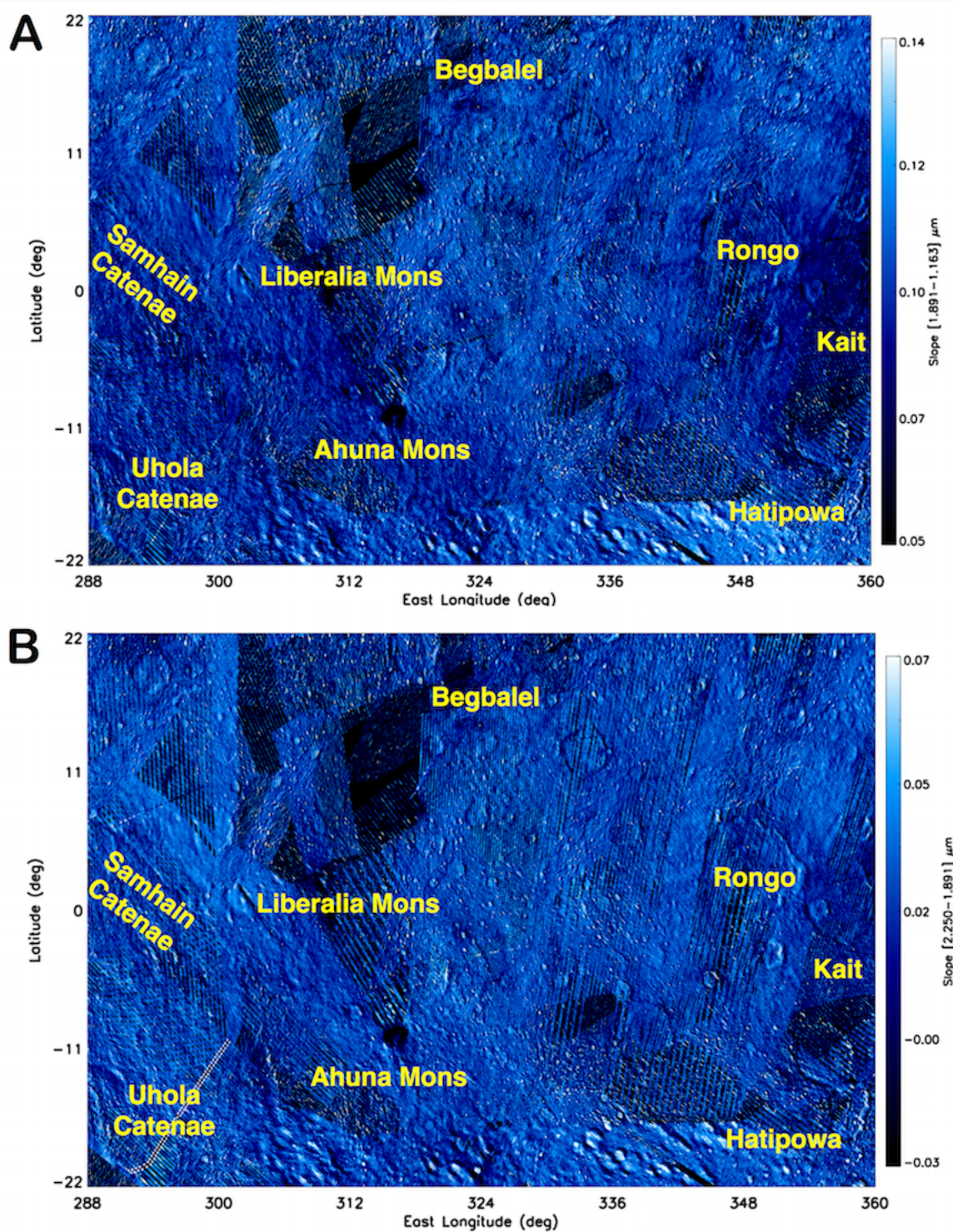
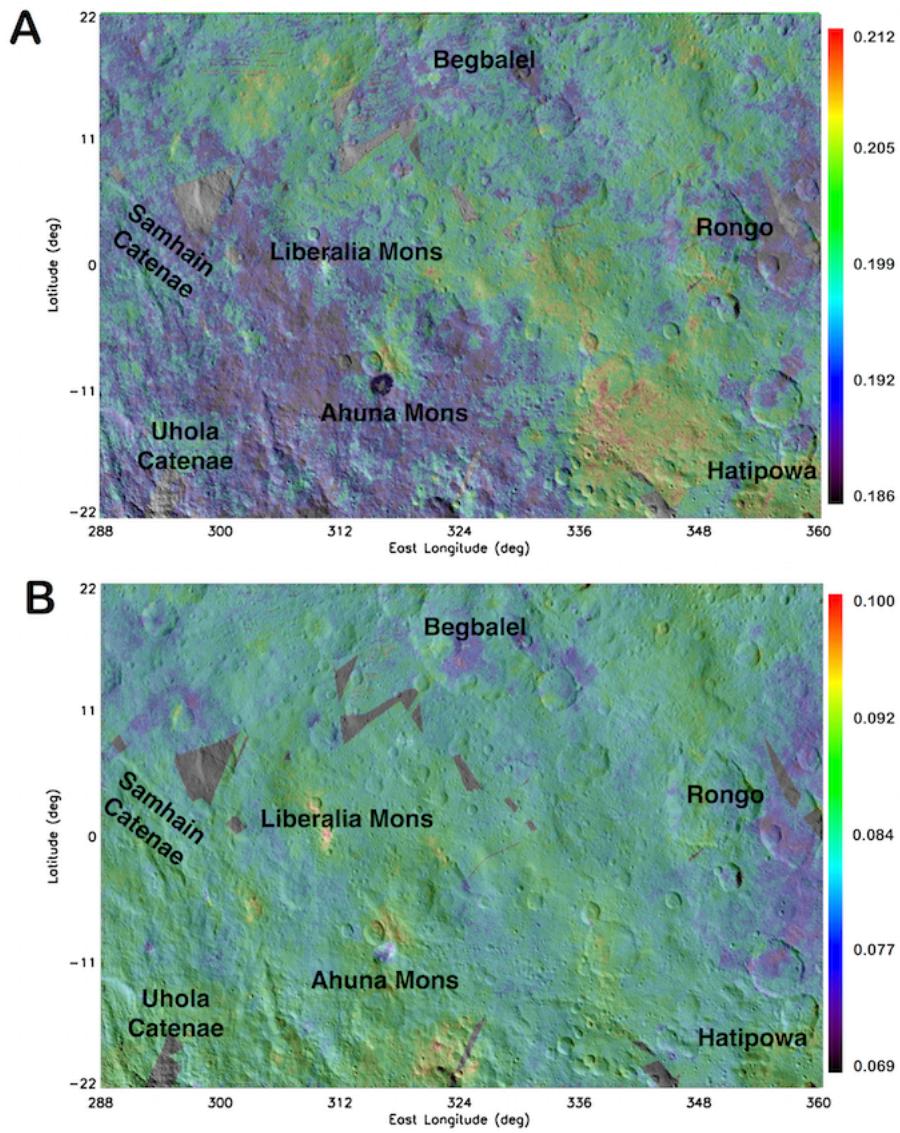


Figure 4



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736 **Figure 5**

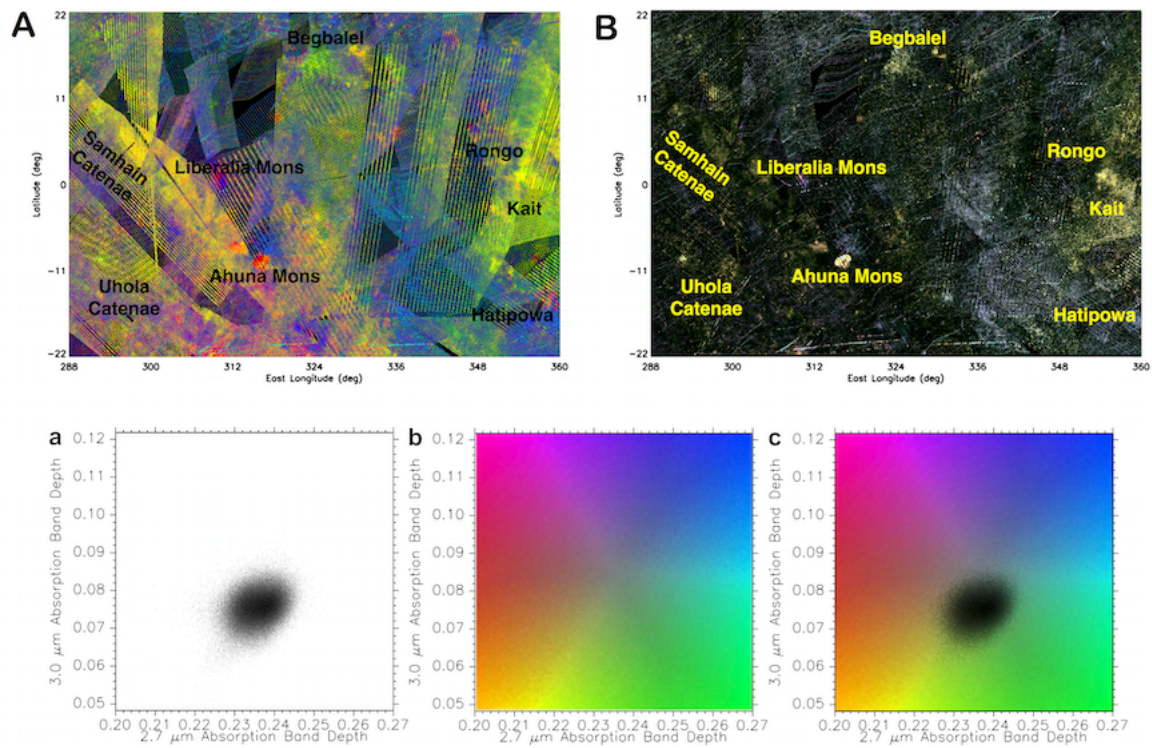


Figure 6

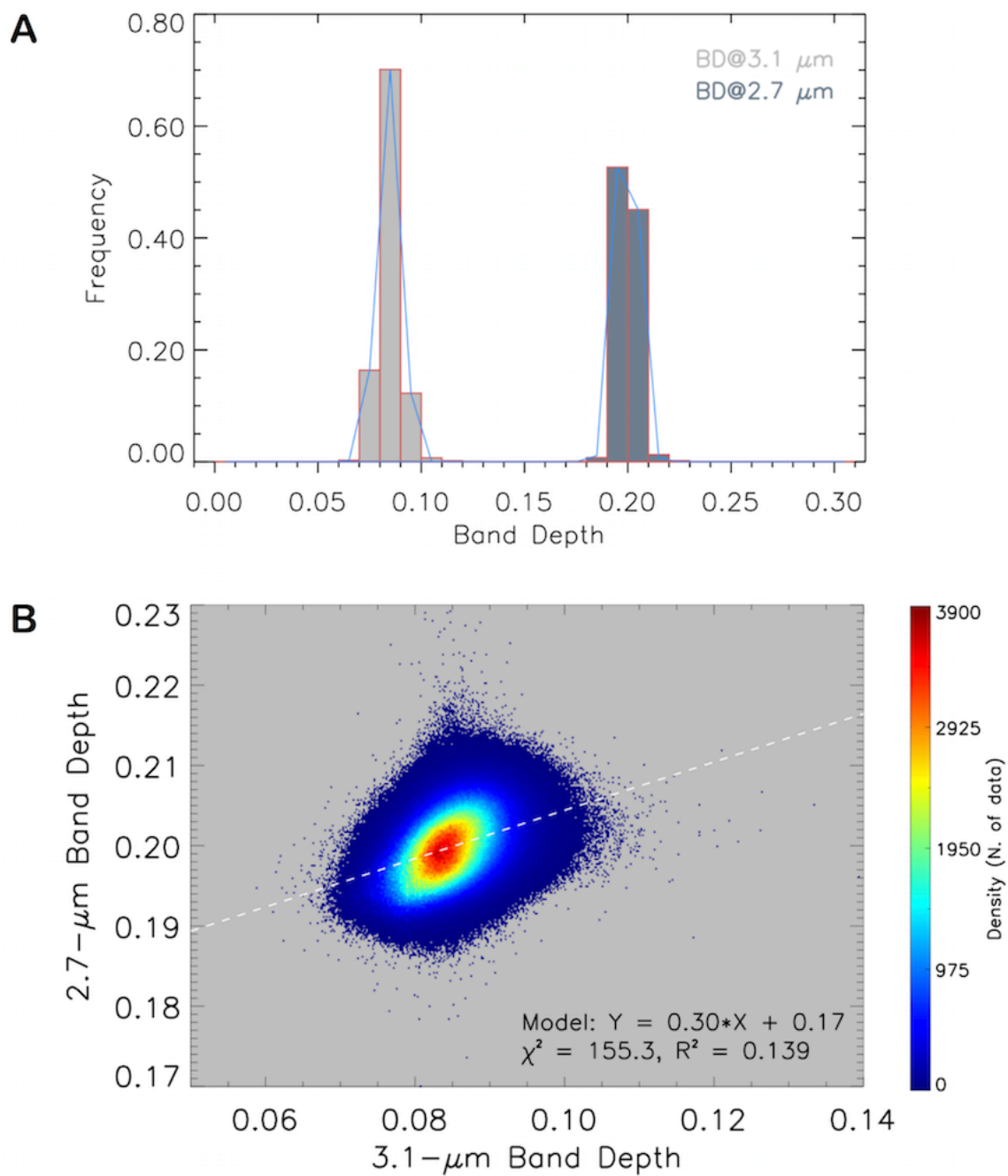


Figure 7

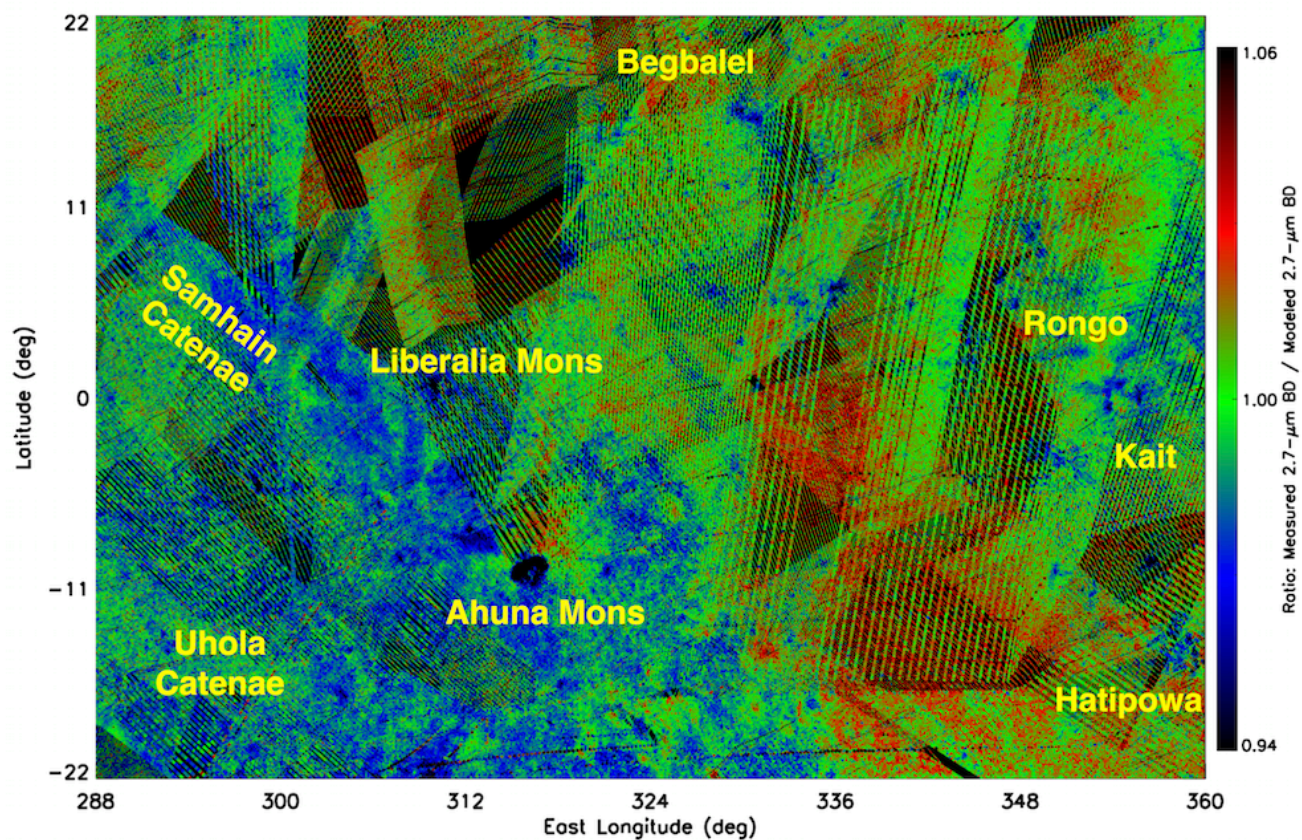


Figure 8