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## Detailed chemical composition analysis of the Soi crater region on Titan

A. Solomonidou, M.J. Malaska, R.M.C. Lopes, A. Coustenis, A.M. Schoenfeld, B. Schmitt, S.P.D. Birch, Alice Le Gall, K. Lawrence, C. Matsoukas, et al.

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# Icarus

## Detailed chemical composition analysis of the Soi crater region on Titan.

--Manuscript Draft--

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<b>Abstract:</b>	<p>The Soi crater region (0° to 60°N, 180°W to -110°W), which includes the well-preserved Soi crater in its center, spans a region from Titan's aeolian-dominated equatorial regions to fluvially-dominated high northern latitudes. This provides a rich diversity of landscapes, one that is also representative of the diversity encountered across Titan. Schoenfeld et al. (2023) mapped this region at 1:800,000 scale and produced a geomorphological map showing that the area consists of 22 types of geomorphological units. The Visual and Infrared Mapping Spectrometer (VIMS) coverage of the region enabled the detailed analysis of spectra of 261 different locations using a radiative transfer technique and a mixing model, yielding compositional constraints on Titan's optical surface layer. Additional constraints on composition on the near-surface substrate were obtained from microwave emissivity. We have derived combinations of top surface materials between dark materials, tholins, water-ice, and methane suggesting that dark mobile organic material at equatorial and high latitudes indicates "young" terrains and compositions, while tholin/water-ice mixtures that dominate areas around latitude 35°N show a material that is older plains deposits that we interpret to be the end stage of aeolian and fluvial transport and deposition. We found no spectral evidence of CO<sub>2</sub>, HC<sub>3</sub>N, and NH<sub>3</sub> ice. We use the stratigraphic relations between the various mapping units and the relation between the geomorphology and the composition of the surface layers to build hypotheses on the origin and evolution of the regional geology. We suggest that sedimentary deposits, likely aeolian, are dominant in the region with fluvial activity and leaching changing the nature of the top surfaces of the midlatitude areas of the Soi crater region.</p>
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<b>Response to Reviewers:</b>	

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**Detailed chemical composition analysis of the Soi crater region on Titan.**  
**Icarus**

**Responses to the Editor and the reviewers**

*Dear Dr Solomonidou,*

*Thank you for submitting your manuscript to Icarus. I have received comments from a reviewer on your revised manuscript. The reviewer makes two final recommendations for minor updates to the manuscript, and I agree with these. I invite you to resubmit your manuscript after addressing the comments below. Please resubmit your revised manuscript by **Jul 21, 2024**.*

*Kind regards,*

*Amanda Hendrix*  
*Editor*  
*Icarus*

**Response:** Dear Dr Hendrix,

We have carefully considered the reviewer's two comments and have made the necessary revisions to comply with the recommendations. We believe that the revisions satisfactorily address all the reviewers' concerns.

Once again, we appreciate the constructive feedback from the reviewers and the editorial team. Thank you for your time and consideration.

Sincerely,  
Anezina Solomonidou

**Reviewer #4:**

*I have read the version 4 of this paper. The authors have taken my comments on version 3 into account. Most of my concerns have been addressed. However, I still disagree on two points:*

*1- the quality of the fits - I still think that it is problematic. It may be the VIMS calibration, the RT model, the lack of a component in the spectral library, ... Anyway, I think that this observation (misfit at low wavelength) should be discussed. The conclusion is that further work is needed to understand the misfit. There is nothing else that the present study can do about it.*

**Response:** Yes, we agree with you and we had already placed cautionary comments in our article. Following your suggestion we have now added the following text: (page 15) 'The mismatch, especially at the shorter wavelengths, is indicative of the limitations set by the VIMS data, the modeling, and the variability of the material library compared to the expected complexity of Titan's surface.' and 'Further work on the Cassini data, along with the advanced development of tools for their processing and additional data from future missions (e.g., Dragonfly) and observations (e.g., JWST), will help us better understand the reasons behind these mismatches and provide solutions for improved fits between the albedos and the simulated surface mixtures.'

*2- H<sub>2</sub>O. As mentioned in previous reviews, the emissivity data are not consistent with the interpretation of the VIMS data. The comparison between figures 7 and 8 illustrates the difference. In Figure 8 (emissivity), low emissivity (water ice) is found in the southeast corner. In Figure 7 (spectral mixing from VIMS data), H<sub>2</sub>O is found at the northeast (20-60 N; 110 W)*

*of the domain and not in the southeast corner (0-10 N, 120 -110 W). This is disturbing. I think that the paper does not address this simple observation very well.*

**Response:** You are right, we have added text to address this observation. (page 20): ‘However, a notable difference between the emissivity and VIMS albedo results is the inconsistency in the major constituent of the mixtures at the southeast ‘corner’ of the Soi crater region of interest. Here, the emissivity data indicate a major water ice constituent (Fig. 8), while VIMS data suggest an organic one, specifically tholin-like material (Figs. 7a and 7b).’

*Otherwise, the paper reads well.*

**Response:** We would like to thank the reviewer for the time and effort in reviewing our work. We have carefully addressed both comments

**Highlights:**

- Titan's compositional evolution cycle includes aeolian transport and leaching.
- Areas around latitude 35°N are dominated by tholin and ice-like spectral signatures
- The midlatitudes are composed of end-stage materials that were subjected to rainfall.
- Empty lakes at the midlatitudes have same composition as the northern empty lakes.

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

## Detailed chemical composition analysis of the Soi crater region on Titan

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## 30 **Abstract**

31 The Soi crater region (0° to 60°N, 180°W to -110°W), which includes the well-preserved Soi crater  
32 in its center, spans a region from Titan’s aeolian-dominated equatorial regions to fluvially-  
33 dominated high northern latitudes. This provides a rich diversity of landscapes, one that is also  
34 representative of the diversity encountered across Titan. Schoenfeld et al. (2023) mapped this  
35 region at 1:800,000 scale and produced a geomorphological map showing that the area consists of  
36 22 types of geomorphological units. The Visual and Infrared Mapping Spectrometer (VIMS)  
37 coverage of the region enabled the detailed analysis of spectra of 261 different locations using a  
38 radiative transfer technique and a mixing model, yielding compositional constraints on Titan’s  
39 optical surface layer. Additional constraints on composition on the near-surface substrate were  
40 obtained from microwave emissivity. We have derived combinations of top surface materials  
41 between dark materials, tholins, water-ice, and methane suggesting that dark mobile organic  
42 material at equatorial and high latitudes indicates “young” terrains and compositions, while  
43 tholin/water-ice mixtures that dominate areas around latitude 35°N show a material that is older  
44 plains deposits that we interpret to be the end stage of aeolian and fluvial transport and deposition.  
45 We found no spectral evidence of CO<sub>2</sub>, HC<sub>3</sub>N, and NH<sub>3</sub> ice. We use the stratigraphic relations  
46 between the various mapping units and the relation between the geomorphology and the  
47 composition of the surface layers to build hypotheses on the origin and evolution of the regional  
48 geology. We suggest that sedimentary deposits, likely aeolian, are dominant in the region with  
49 fluvial activity and leaching changing the nature of the top surfaces of the midlatitude areas of the  
50 Soi crater region.

## 51 **1 Introduction**

52 The surface of Saturn’s moon Titan has been revealed by the Cassini-Huygens spacecraft  
53 to be geologically complex with both exogenic and putative endogenic processes modifying its  
54 appearance. Titan’s dense atmosphere and active methane cycle has enabled aeolian, fluvial,  
55 pluvial, and lacustrine processes, causing erosion and deposition. Few impact craters are seen,  
56 attesting that the surface is geologically young (e.g., Wood et al., 2010; Hedgepeth et al., 2020).  
57 Tectonism and possibly cryovolcanism have also contributed to surface modification (Jaumann et  
58 al., 2009; Mitri et al., 2008, 2010; Radebaugh et al., 2007; Lopes et al., 2013; 2019; Wall et al.,  
59 2009; Nelson et al., 2009; Solomonidou et al., 2013; 2016; Sohl et al., 2014; Wood and Radebaugh,  
60 2020). The rich variety of geologic features on Titan and how the processes have dominated  
61 different latitudes have been discussed in previous works. For example, lakes and seas are present  
62 at high latitudes (e.g., Stofan et al., 2007; Bratsolis et al., 2012; Birch et al., 2016), while dunes of  
63 organic materials are concentrated at low latitudes (Lorenz et al., 2006; Radebaugh et al., 2008;  
64 Lopes et al., 2010; Rodriguez et al., 2014). Fluvial channel networks are present across large areas  
65 of the surface (Jaumann et al., 2008; Malaska et al., 2011; Langhans et al., 2012; Burr et al., 2013;  
66 Radebaugh et al., 2016; Miller et al., 2021), with a rich diversity in morphology (Burr et al., 2013;  
67 Miller et al., 2021), and are both liquid-filled (Poggiali et al., 2016) and dry. The mountainous and  
68 hummocky units represent remnants of an older crust, making them the oldest exposed unit on  
69 Titan, and they mostly appear in the equatorial zones and small areas all over the globe (Williams  
70 et al., 2011; Lopes et al., 2020a; Malaska et al., 2016a; 2020; Schoenfeld et al., 2021). Organic  
71 materials, produced by high-altitude photochemistry of methane and nitrogen in Titan’s  
72 atmosphere, cover much of Titan’s surface (Wilson and Atreya, 2004; Lavvas et al., 2008;  
73 Krasnopolsky, 2009; Clark et al., 2010; Solomonidou et al., 2018; 2020a). The buildup of these  
74 organic materials is evidenced by large standing dissected plateaux elevated by hundreds of meters

75 (Malaska et al., 2020). The midlatitudes of Titan are dominated by undifferentiated plains (Lopes  
76 et al., 2016; 2019; 2020) which are interpreted as being sedimentary in nature and likely formed  
77 by aeolian processes (Malaska et al., 2016b). Titan’s latitudinal dependence for composition of the  
78 upper surface layer (Solomonidou et al., 2018), as well as patterns of wind deposition (Malaska et  
79 al., 2016b), show that, for both hemispheres, winds may transport material from both equatorial  
80 regions and high latitudes towards a zone at  $\sim 35^\circ$ . That zone, at the midlatitudes may represent a  
81 ‘sink’, where materials are deposited as undifferentiated plains (Lopes et al., 2016; Malaska et al.,  
82 2016b; Solomonidou et al., 2020a).

83 The Soi crater region is scientifically valuable as it straddles the equatorial, midlatitude,  
84 and northern regions of Titan. The present study on the composition complements the  
85 geomorphological study of Schoenfeld et al. (2023). Our compositional map for this region is  
86 created using a radiative transfer code with Visual and Infrared Mapping Spectrometer (VIMS)  
87 data that help estimate the haze contribution to the data and extract surface information that are  
88 later matched to surface component mixture simulations (Hirtzig et al., 2013; Bonnefoy et al.,  
89 2016; Solomonidou et al., 2014; 2018; 2020a;b). The goal of this paper is to bring constraints on  
90 the formation and evolution of the selected area through the combination of the geomorphological  
91 and compositional maps of the Soi crater region. The maps will help reveal the types and extent  
92 of the geomorphologic units and the differences in nature of the top layers of the surface, and to  
93 infer the geological processes responsible for their formation and evolution. Our compositional  
94 mapping follows the methods described in Solomonidou et al. (2014; 2018; 2020a;b). Our efforts  
95 here are part of a global compositional mapping project that is currently in progress (Solomonidou  
96 et al., 2022), attempting to improve our knowledge of Titan’s complex systems.

97

## 98 **2 Geologic Setting**

99 The Soi crater region was defined in Schoenfeld et al. (2023) as the area spanning from  
100 longitude  $180^\circ$  W to  $110^\circ$  W and from latitude 0 to  $60^\circ$  N and the area contained in this region  
101 amounts to  $\sim 8 \times 10^6$  km<sup>2</sup> ( $\sim 9.7\%$  of Titan’s surface). This region is geomorphologically mapped in  
102 detail and presented in the same article. For the production of the map by Schoenfeld et al. (2023)  
103  $\sim 5.6\%$  of the total surface area was mapped by using high resolution Synthetic Aperture Radar  
104 (SAR) data and the rest of the area was covered by non-SAR data (microwave emissivity, Imaging  
105 Science Subsystem -ISS, and VIMS), and mapped at lower resolution. For VIMS and the  
106 compositional mapping efforts, the area that was covered with data compatible and adequate to  
107 our radiative transfer modeling (detailed in section 3) spanned approximately  $5.4 \times 10^6$  km<sup>2</sup>, which  
108 corresponds to  $\sim 6.5\%$  of Titan’s total surface. The Soi crater region contains 22 distinct  
109 geomorphological units many of which were found in the Afekan (Malaska et al., 2016a) and  
110 South Belet regions (Schoenfeld et al., 2021).

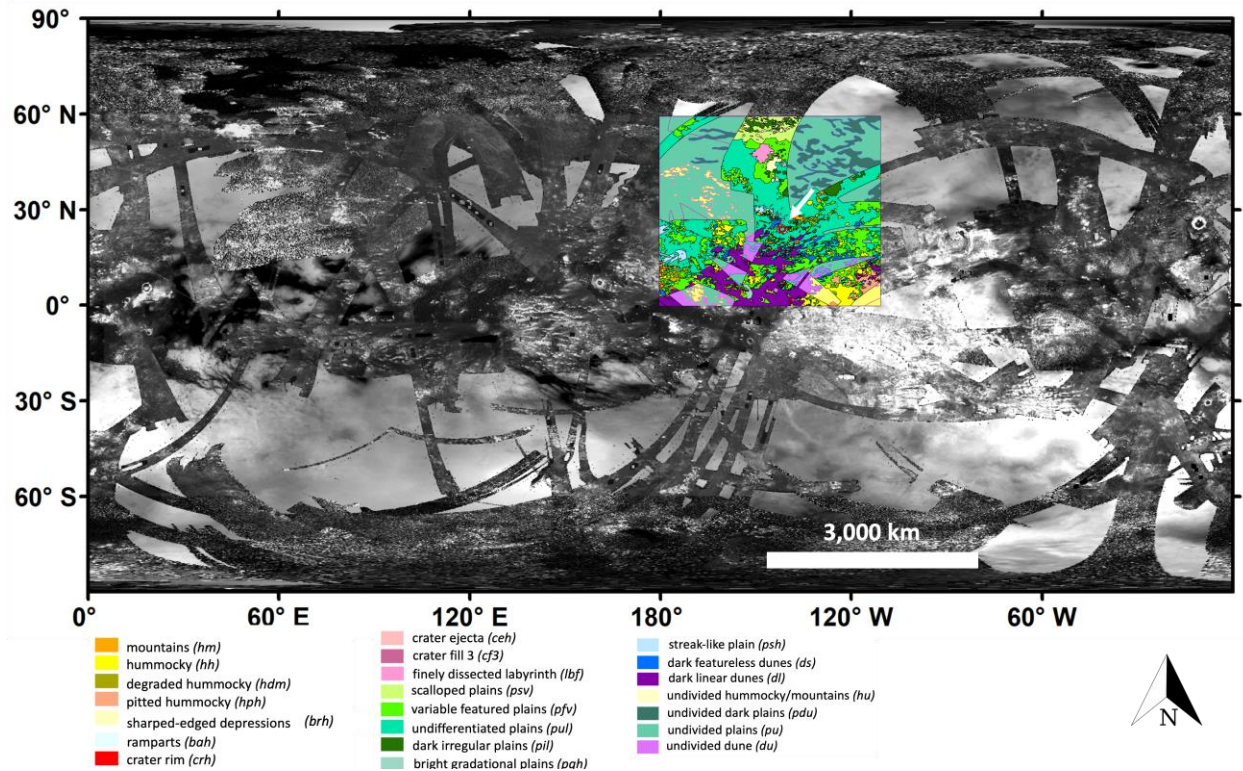
111 The geomorphological map presented in Schoenfeld et al. (2023) used SAR and non-SAR  
112 datasets including altimetry, Radiometry-Emissivity, ISS, and VIMS (Fig. 1). All the different  
113 Cassini data used to create the geomorphological map of the Soi crater region (SAR, HiSAR,  
114 SARTopo and Digital Terrain Model, emissivity, VIMS, and ISS data) can be seen in Figure 2 of  
115 Schoenfeld et al. (2023). The 22 geomorphological units identified include features of empty lakes,  
116 mountains, dunes, craters, labyrinth, and vast plains (Table 1). The Soi crater region is dominated  
117 by plains, matching the general trend around Titan’s globe (see Lopes et al., 2020), followed by  
118 dunes, mountainous terrains, and finally very few craters and empty sharp-edged depressions

119 (SEDs) (Table 1). As for most of Titan, impacts have been erased by more recent geological  
 120 processes, likely those that form dunes and plains.

121  
 122 **Table 1.** Terrain class, terrain units, terrain unit code found in the Soi crater region. Details,  
 123 locations, and descriptions of the units are in Table 1 of Schoenfeld et al. (2023). The letter codes  
 124 followed here are based on mapping efforts that have followed the general principles of previous  
 125 Titan mapping and other planetary mapping efforts (Greeley and Batson, 1990; Greeley et al.,  
 126 2000; Patterson et al., 2010; Williams et al., 2014; Lopes et al., 2016; 2020; Malaska et al., 2016;  
 127 2020; Schoenfeld et al., 2021; 2023).

Terrain class/ % of total area	Terrain unit name and code
<b>Plains (73%)</b>	Undifferentiated plains ( <i>pul</i> )
	Variable plains ( <i>pfv</i> )
	Scalloped plains ( <i>psv</i> )
	Dark irregular plains ( <i>pil</i> )
	Streak-like plains ( <i>psh</i> )
	Bright gradational plains ( <i>pgh</i> )
	Undivided plains ( <i>pu</i> )
	Undivided dark plains ( <i>pdu</i> )
<b>Dunes (14%)</b>	Featureless sand sheets ( <i>ds</i> )
	Linear dunes ( <i>dl</i> )
	Undivided dunes ( <i>du</i> )
<b>Mountains / Hummocky / Labyrinth (12%)</b>	Mountain ( <i>hm</i> )
	Hummocky ( <i>hh</i> )
	Degraded hummocky ( <i>hdm</i> )
	Pitted hummocky ( <i>hph</i> )
	Undivided mountain chains/hummocky areas ( <i>hu</i> )
<b>Craters (&lt;1%)</b>	Crater rim ( <i>crh</i> )
	Crater ejecta ( <i>ceh</i> )
	Crater fill 3 ( <i>cf3</i> )
<b>Lakes (&lt;1%)</b>	Sharp-edged depression ( <i>bse</i> )
	Ramparts ( <i>brh</i> )

128



129

130 **Figure 1.** Geomorphological map of the Soi crater region (adapted from Schoenfeld et al., 2023)  
 131 in global context. Geomorphological map for all SAR and non-SAR data at zero transparency (map  
 132 layer fully opaque), same color scheme as the global geomorphological map of Titan in Lopes et  
 133 al. (2020). The arrow points to the Soi crater. The background map is a global mosaic of Titan  
 134 created from Imaging Science Subsystem (ISS) data (USGS Astrogeology Science Center).

135

### 136 3 Compositional mapping

137 Titan's surface composition remains, to this day, largely a mystery. Due to both  
 138 atmospheric effects and spectral degeneracies, we have so far been prevented from making  
 139 quantitative and accurate estimates of material concentrations within the numerous and varied  
 140 geologic units on Titan's surface. This is a complex situation that can only be improved in a step-  
 141 by-step approach in which every new constraint brings useful additional information, while  
 142 waiting for new observations from ground-based facilities or *in situ* data from space missions like  
 143 Dragonfly (e.g., Tobie et al., 2014; Lorenz et al., 2021; Barnes et al., 2021; Sulaiman et al., 2021;  
 144 Rodriguez et al., 2022). There are, however, select windows through Titan's atmosphere in the  
 145 near-infrared where the methane absorption is reduced (e.g., Barnes et al., 2005; Corlies et al.,  
 146 2021). Due to Titan's complex atmosphere and processes therein, we apply a radiative transfer  
 147 code to Cassini VIMS data in order to tackle as well as possible the issue of lingering methane  
 148 absorption and scattering of atmospheric components.

149 For the chemical compositional mapping, we used methods that have been successfully  
 150 used in the past on VIMS data (Bonney et al., 2016; Lopes et al., 2016; Malaska et al., 2016a;  
 151 Brossier et al., 2018; Solomonidou et al., 2014; 2016; 2018; 2020a,b), to account for the  
 152 atmospheric contribution to the data and extract the actual surface information in the form of

153 albedo values and spectral responses. Further, similar to Solomonidou et al. (2018), where the first  
154 attempt of constraining the chemical composition of all major Titan geomorphological units was  
155 made, in addition to the compositional analysis of one specific unit, the impact craters  
156 (Solomonidou et al., 2020a), here we provide a compositional analysis of the entire Soi crater  
157 region in greater detail than in the previous efforts and for a significantly larger number of units  
158 and locations. Efforts to spectrally analyze Titan's vast areas and constrain their composition can  
159 be found in Nelson et al. (2006), McCord et al. (2006; 2008), Barnes et al. (2008), Brown et al.  
160 (2008), Clark et al. (2010), Soderblom et al. (2010), MacKenzie et al. (2014), Rodriguez et al.  
161 (2014), Brossier et al. (2018), Griffith et al. (2019), Coutelier et al. (2021) and others. All of these  
162 studies have analyzed VIMS data. Some of them have utilized radiative transfer codes (e.g., Coutelier et  
163 al., 2021) for their data analyses, while others have employed geophysical and remote sensing tools and  
164 methods such as Principal Component Analysis (PCA) (e.g., Griffith et al., 2019) and spectral ratios (e.g.,  
165 Barnes et al., 2008). These methods are often employed to highlight differences between features and to  
166 reduce the effect of varying light reflectance intensities. In Coutelier et al. (2021), the radiative transfer  
167 code is utilized to factor in atmosphere scattering and absorption, thereby eliminating atmospheric effects  
168 and discrepancies caused by observational geometries. The ultimate outcome is the retrieval of atmospheric  
169 albedos across all atmospheric windows. Their findings underscore a significant observation, which is  
170 compatible to findings of this present work: the relationship between water ice and VIMS 'dark blue' and  
171 'bright blue' areas is not as straightforward as previously believed (Barnes et al., 2007a, 2007b).

172 Our chemical composition map was created using the measurements of VIMS through our  
173 radiative transfer code (RT) and spectral deconvolution analysis. We recognize that the spectral  
174 analysis is only of the very thin optical layer (tens of microns) that covers the surface of Titan. To  
175 take into account the material below the optical covering, in our interpretations of the geological  
176 history of the area we also use the microwave emissivity measurements that probe the surface to  
177 greater depths (tens of centimeters). Microwave emissivity can be used to constrain the  
178 composition in depths that IR is unable to reach. Indeed, the radiometry provides a measure of the  
179 averaged emissivity of the near subsurface down to a depth that can be approximately defined as  
180 the electrical skin depth (Janseen et al., 2016). The sounding depth has been estimated based on  
181 the seasonal thermal signature in Janssen et al. (2009; 2016) and it is of the order of 40 cm - 1 m  
182 in the radar dark terrains, and to 200 m in liquid methane. This largely depends on the microwave  
183 transparency of the material, while the presence of high dielectric constant materials and/or volume  
184 scattering due to the presence of structures in the subsurface, are considered factors that decrease  
185 the emissivity values (Janssen et al., 2016).

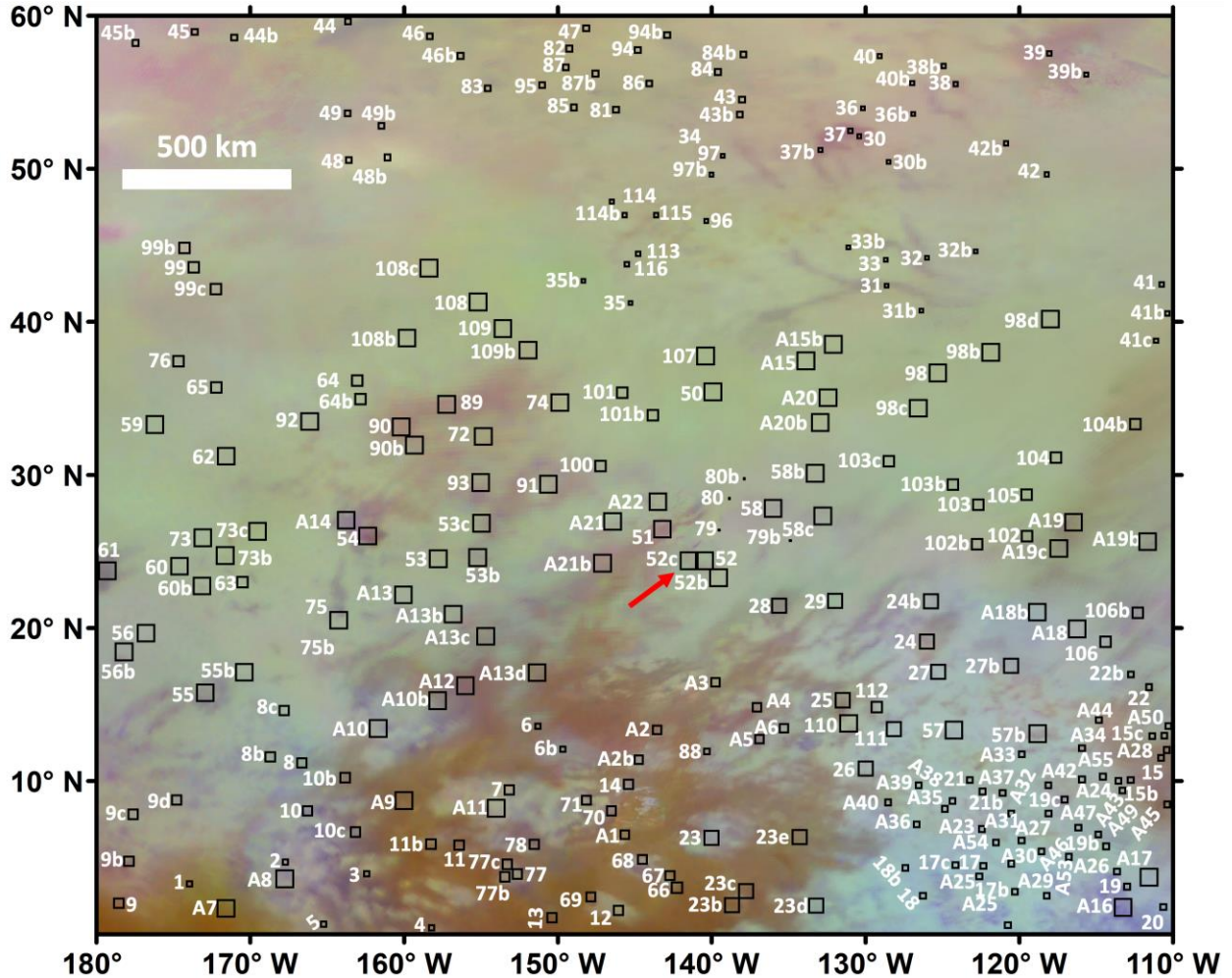
### 186 3.1 Radiative Transfer Technique and Mixing Model

187 The compositional results are extracted through a series of analyses of VIMS data. We have  
188 analyzed 261 different locations from within the Soi crater region using 14 VIMS datacubes from  
189 8 different Cassini flybys (Table 2; Figure 2). The selection of our 261 regions of interest (RoIs)  
190 was made after carefully examining the available VIMS datacubes compatible to our RT  
191 approximation and was based on the identification of pixels that thoroughly include different  
192 geomorphological units as described in Schoenfeld et al. (2013) in good resolution. We then used  
193 our RT code to extract surface albedos from the VIMS data (Hirtzig et al., 2013; Solomonidou et  
194 al., 2014;2016; 2018; 2020a;b).

195  
196 **Table 2.** Selected Cassini/VIMS datacube observations including flybys, dates of acquisition,  
197 product IDs, and cube properties (angles of incidence  $i$ , emergence  $e$ , and phase  $\alpha$ ; spatial  
198 resolution res).

Flyby	Date	Selected pixels with numbers as shown in Fig. 2 and product IDs	Datacube Properties Geometry-Spatial Resolution ( <i>i,e,a,res/pxl</i> )
Tb	12/2004	79-80: 1481629409	<i>i</i> : 52-53°, <i>e</i> : 15-17°, <i>a</i> : 36-37°, res: 03 km
T08	10/2005	A7-A31, A33, 98: 1509148649 50-58, 107-110: 1509149009 59-62, 72-75, 89-93: 1559085140	<i>i</i> : 30-57°, <i>e</i> : 09-46°, <i>a</i> : 23-24°, res: 46 km <i>i</i> : 34-60°, <i>e</i> : 26-42°, <i>a</i> : 22-23°, res: 45 km <i>i</i> : 49-60°, <i>e</i> : 26-42°, <i>a</i> : 25-26°, res: 39 km
T10	01/2006	1-6: 1516007480	<i>i</i> : 36-49°, <i>e</i> : 01-12°, <i>a</i> : 37-38°, res: 14 km
T12	03/2006	15-22: 1521407900 23-29, 111-112: 1521405451 A1-A6, A32, A34-A55: 1521402363	<i>i</i> : 29-37°, <i>e</i> : 34-55°, <i>a</i> : 65-66°, res: 15 km <i>i</i> : 45-57°, <i>e</i> : 19-38°, <i>a</i> : 64-65°, res: 38 km <i>i</i> : 54-59°, <i>e</i> : 11-41°, <i>a</i> : 63-64°, res: 23 km
T31	05/2007	63-66, 76, 99-106: 1559081653	<i>i</i> : 48-59°, <i>e</i> : 37-51°, <i>a</i> : 26-27°, res: 29 km
T77	06/2011	7-12, 14, 77-78b: 1687307753	<i>i</i> : 10-38°, <i>e</i> : 27-58°, <i>a</i> : 21-22°, res: 25 km
T97	01/2014	30-36, 96-97, 113-116: 1767303982 33b, 37-42: 1767303262 43-49, 81-88, 94-95: 1767301842	<i>i</i> : 33-49°, <i>e</i> : 10-28°, <i>a</i> : 51-54°, res: 10 km <i>i</i> : 43-60°, <i>e</i> : 08-30°, <i>a</i> : 52-53°, res: 12 km <i>i</i> : 32-44°, <i>e</i> : 11-22°, <i>a</i> : 55-56°, res: 16 km
T113	09/2015	13, 67-71: 1822165321	<i>i</i> : 37-59°, <i>e</i> : 02-09°, <i>a</i> : 57-58°, res: 14 km

199  
200



204 selected at each location based on their spatial resolution (see Table 2). The red arrow indicates  
205 the location of the Soi crater. North is at the top.

206  
207 Our RT code (Hirtzig et al., 2013) is a plane-parallel code based on a Spherical Harmonic  
208 Discrete Ordinate Method solver (SHDOMPP) (Evans, 2007) that incorporates: (a) the vertical  
209 profiles of temperature and pressure provided by the Huygens Atmospheric Structure Instrument  
210 (HASI) (Fulchignoni et al., 2005); (b) the methane vertical mixing ratio from the Gas  
211 Chromatograph Mass Spectrometer (GCMS) (Niemann et al., 2010); (c) a uniform CO mole  
212 fraction equal to  $4.5 \times 10^{-5}$  based on Cassini/CIRS measurements (de Kok et al., 2007); (d)  
213 atmospheric opacity sources from aerosols and gases: Rayleigh scattering from  $N_2$  and  $CH_4$  (Peck  
214 and Khanna, 1966; Weber, 2003); collision-induced absorption by nitrogen ( $N_2$ ) and hydrogen  
215 ( $H_2$ ) (McKellar et al. (1989); Lafferty et al. (1996); lines for methane (Campargue et al., 2015;  
216 TheoReTS - Rey et al., 2018) and its isotopologues (e.g.,  $^{12}CH_4$ ,  $^{13}CH_4$ ,  $^{12}CH_3D$ ) (HITRAN2020 -  
217 Rothman et al., 2013; Gordon et al., 2022); lines for CO and  $C_2H_2$  isotopologues (GEISA2009 -  
218 Jacquinet-Husson et al., 2011) with the use of correlated- $k$  absorption coefficients as described in  
219 Hirtzig et al. (2013). Considering all components (a-d), the code analyses the VIMS data and  
220 produces simulations of the surface albedo with various haze opacities.

221 The results are then calibrated with respect to the albedo measurements derived by the  
222 Descent Imager Spectral Radiometer (DISR) at the Huygens landing site (HLS), which we use as  
223 a reference area and a calibration tool. Given that the haze extinction profile reference is adjusted  
224 to the measurements from DISR, the haze contribution to the VIMS data at the landing site of  
225 Huygens is defined as 100%. By iteration for the best possible fit, the code derives the haze  
226 contributions with an absolute accuracy of  $\pm 5\%$  (Hirtzig et al., 2013). After estimating the haze  
227 population at all window wavelengths, the surface albedos are extracted at full spectral resolution  
228 and in weighted averages over each window's wavelength range (Tomasko et al., 2008; Hirtzig et  
229 al., 2013). In a weighted average, each data point value from within each of the 8 atmospheric  
230 windows is multiplied by an assigned weight, which is then summed and divided by the number  
231 of data points. For this reason, a weighted average can improve the data's accuracy. In this current  
232 analysis, we calculated single points of weighted averages of the surface albedo within the  
233 windows, with larger weights for channels with higher transmittance around the center. The  
234 spectral resolution (Full Width at Half Maximum, FWHM) is about 13 nm below 2.0  $\mu m$ , increases  
235 up to 22 nm at 4.2  $\mu m$ , and decreases to 18 nm at 4.8  $\mu m$  (Brown et al., 2004). An example of  
236 weighted averages of the surface albedos in the atmospheric windows compared to the full  
237 resolution surface albedo spectrum in the 0.89–5.2  $\mu m$  of the Visual and Infrared Mapping  
238 Spectrometer range can be found in Figure 5 of Solomonidou et al. (2018).

239 In our RT code and the extraction of surface albedos, we consider several uncertainties  
240 calculated and summed at the  $3\sigma$  level including random errors due to noise in the data and due to  
241 propagation of haze retrieval errors, as well as systematic errors due to model, resulting from  
242 uncertainties due to the  $CH_4$  far-wings opacity, the  $CH_4$  linelist, the  $CH_4$  vertical concentration  
243 profile, the aerosol phase function, the aerosol vertical distribution, and the aerosol forced single  
244 scattering albedo. All the details on the error estimation can be found in Section 3.3. in Hirtzig et  
245 al. (2013). In this current analysis we also take into account errors in the existing spectral line  
246 profiles, the haze extinction fit, the data intrinsic noise, which unlike random noise, is not random  
247 but arises from specific characteristics or imperfections in the sensor (McCord et al., 2004) and  
248 the phase function uncertainty. The surface albedos are then inverted with relative errors of 35%,  
249 35%, 26%, 21%, 26%, 50%, 50%, and 43% for the 0.94, 1.08, 1.28, 1.58, 2.03, 2.69, 2.79, 5.00  
250  $\mu m$  windows, respectively. At the longer wavelengths of 2.69-5  $\mu m$ , the uncertainties are larger

251 due to the lower signal to noise ratio (S/N). In any case, the error bars on the best fit of surface  
252 albedos take into account not only S/N limitations, but also errors due to uncertainties on the haze  
253 model (typical error on the extinction is 5%). Since the RT code adopts a plane-parallel and a  
254 Lambertian approximation and for the accuracy of the results, only VIMS data with geometry  
255 observations of both incidence and emergence angles  $<60^\circ$  are selected, with only 15% of the data  
256 selected having incidence or emergence angles  $>50^\circ$  (Table 2). We followed the approach used  
257 previously and in the recent study by Es-Sayeh et. al. (2023) where the authors use the RT code  
258 with the plane-parallel approximation used in this current analysis as well, and recommend the use  
259 of VIMS datacubes with incidence angles up to  $50^\circ$  incidence angle. The phase angle of all  
260 selected datacubes are higher than  $10\text{-}15^\circ$  and up to  $70^\circ$  and hence the surface behaves almost as  
261 Lambertian (Karkoschka et al., 2012). The effects of the phase angle on the I/F value are included  
262 in the error bars on our results (Karkoschka et al., 2012; Solomonidou et al., 2014). The spatial  
263 resolution of our selected datacubes ranges from 3 to 46 km/pixel (Table 2).

264 Finally, we use a linear mixing model, as in previous work (Solomonidou et al., 2018;  
265 2020a), to place semi-quantitative constraints on the relative composition of Titan's surface. The  
266 model includes a selected spectral library of molecules, used as proxies for Titan candidate  
267 materials convoluted to VIMS spectral resolution, in order to examine the compositional properties  
268 of the various regions within the Soi crater region. While some of the specific molecules and  
269 complex carbonaceous materials included in our mixing model library are not expected to be found  
270 on Titan, we have used them to represent complex organic materials. Many of these materials are  
271 biogenic in origin, and through terrestrial diagenetic processes have become chemically  
272 aromatized and converted into complex refractory materials. The purpose of this exercise is not to  
273 imply exact chemical composition, but to constrain the relative types of molecular classes that  
274 could be present.

275 The Titan candidate materials include ices of ammonia ( $\text{NH}_3$ ), carbon dioxide ( $\text{CO}_2$ ), water  
276 ( $\text{H}_2\text{O}$ ), cyanoacetylene ( $\text{HC}_3\text{N}$ ), methane ( $\text{CH}_4$ ), tholins, kerite, asphaltite, three different types of  
277 anthraxolites, and amorphous carbon (Quirico and Schmitt 1997; Grundy and Schmitt 1998;  
278 Grundy et al., 2002; Bernard et al., 2006; Brasse et al., 2015; GhoSST @ SSHADE database).

279 Tholins are laboratory-produced materials which may differ from the complex aerosols  
280 produced in Titan's atmosphere and later processed at the surface by fluvial/pluvial/aeolian  
281 activity. However, their spectral properties have been used in Titan's spectral analyses to simulate  
282 the atmospheric haze content.

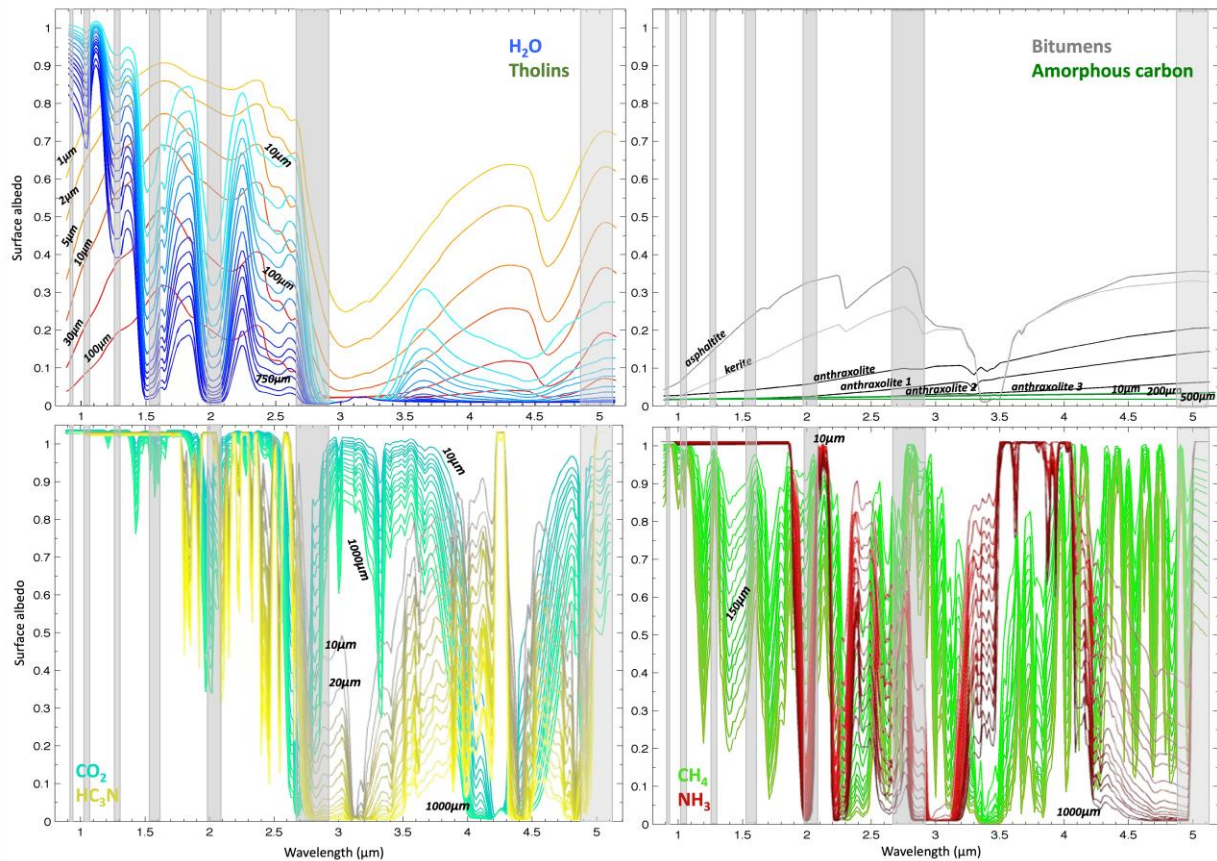
283 We use 'methane' as a representative for any aliphatic hydrocarbon solid including  
284 alkanes, alkynes, and alkenes (e.g., Lora and Ádámkóvics, 2017; Malaska et al., 2017; Faulk et  
285 al., 2017; 2020). These other solid aliphatic materials may be part of the compositional mix,  
286 however, these larger aliphatic materials will not be liquid since at Titan temperatures only  
287 methane, ethane, propane, and 1-butene are liquid. As a proxy for solid materials, methane does  
288 not have measurable significant position shifts (i.e., any shifts are much smaller than VIMS  
289 resolution). In addition, the optical constants of methane remain virtually unchanged between  
290 liquid and solid at 93 K (Grundy et al., 2002). Thus, we use methane as a general proxy for  
291 materials (simple organics) although the spectral and optical constant properties of the actual  
292 materials could be much more complicated.

293 The data of the icy components have been calculated with the 'SPECTRIMAG' radiative  
294 transfer code for granular surfaces (Douté and Schmitt, 1998), in sets of 15 different pathlengths  
295 spanning 2 orders of magnitude. All components in the constituent library are in the VIMS  
296 spectrum and hence simulations with the extracted RT albedos are possible. The mixing model fits  
297 the RT extracted albedos with the most compatible mixture of the proxy constituents and linear  
298 mixtures thereof, inferring at least 4 constituents (Solomonidou et al., 2018; 2020a). The model  
299 provides compositional constraints using the limited number of available atmospheric windows



300 and that entails that there is no unique solution for the mixtures. A perfect fit cannot be achieved  
301 between the simulations and the observations because all radiative transfer codes are incapable of  
302 totally reproducing the complexity of Titan's system (atmosphere, surface, and interactions among  
303 these convoluted elements) and no simple mixture of components can reproduce what exists on  
304 the surface of Titan. Our method tests to what extent the available observations (absolute values  
305 and spectral shape) can be match with these basic constituents. The code output includes estimated  
306 errors of the derived abundances of the different components of the mixture.

307 Bitumens are used as proxies to lower the total surface albedo (Moroz et al., 1998; Lellouch et  
308 al., 2004; Court et al., 2006; Combe et al., 2007; Hirtzig et al., 2012) as it is expected to be low for  
309 Titan. Bitumen on Earth is a very complex intractable mixture containing many hydrocarbon and  
310 functionalized hydrocarbon components. It derives from coal and petroleum residues which in turn  
311 derived from diagenetically processed humic acids, steroids, and wax lignins from buried (usually  
312 vegetative) biologically produced organic matter. It is not likely that bitumen as produced on Earth  
313 would be exactly present on Titan. However, in the absence of another good analogue for dark  
314 materials we have applied this component as a proxy in our simulations. In particular, bitumen  
315 contains a large amount of naphthene aromatics (naphthalene), consisting of partially  
316 hydrogenated polycyclic aromatic compounds. We use these as a proxy for complex mixtures of  
317 Titan aromatic molecules that fused and linked such as (for fused) phenylacetylene, naphthalene,  
318 and phenanthrene (Abplanalp et al., 2019) and linked aromatics such as biphenyl, terphenyl and  
319 higher homologs. All solid small-molecule organics included in the spectral library are in 15 grain  
320 sizes (10, 20, 30, 40, 50, 75, 100, 150, 200, 250, 300, 400, 500, 750, and 1,000  $\mu\text{m}$ ), the laboratory  
321 tholins in 6 grain sizes (1, 2, 5, 10, 30, and 100  $\mu\text{m}$ ), and the amorphous carbon in 3 grain sizes  
322 (10, 200, and 500  $\mu\text{m}$ ) (Quirico and Schmitt, 1997; Grundy and Schmitt 1998; Grundy et al., 2002;  
323 Bernard et al., 2006; GhoSST @ SSHADE solid spectroscopic database). Hence, in total we  
324 examined 90 different spectral possibilities. The spectra data used in this study in the VIMS range  
325 can be seen in Figure 3.



327

328 **Figure 3.** Spectra data of candidate components used in this work adapted from Solomonidou et  
 329 al. (2020a). H<sub>2</sub>O in shades of blue; laboratory tholins in shades of orange; bitumens in gray, and  
 330 amorphous carbon in dark green; CO<sub>2</sub> in shades of turquoise, and HC<sub>3</sub>N in shades of yellow; CH<sub>4</sub>  
 331 in shades of light green, and NH<sub>3</sub> in shades of red. These spectra are plotted in the spectral range  
 332 of VIMS at different grain sizes (Bernard et al. 2006; Brassé et al. 2015; GhoSST database,  
 333 <http://ghosst.osug.fr>). The light gray columns correspond to Titan's atmospheric windows.  
 334

### 335 3.2 Haze Estimations and Surface Albedos

336 The VIMS datacubes shown in Table 2 were acquired at different observational properties  
 337 and at different times during the Cassini mission (Tb – T113: 2004-2015). The analyzed VIMS  
 338 pixels from the 261 different locations are expected to include different atmospheric effects, which  
 339 is something that has been found to occur even at adjacent pixels from within the same VIMS  
 340 datacube (Solomonidou et al., 2016; 2018). Indeed, the analyses of the VIMS data from the various  
 341 locations within the SoI crater region showed that the haze contributions to the VIMS data ranges  
 342 from 70-130% ( $\pm 5\%$ ) with respect to the Huygens Landing Site DISR measurements used a  
 343 calibration point (Karkoschka & Tomasko, 2010). In particular, the haze contribution to the data  
 344 seems to present a relative dependance with latitude. Datacubes from flybys Tb, T08, T10, T12,  
 345 and T77 that cover mostly low to mid latitudes when treated with RT the haze estimation ranges  
 346 between 70-110%, while from T31 and T97 that cover mostly higher latitudes range from 100-  
 347 130%.

348 The examples of extracted surface albedos in the form of weighted averages are shown in  
349 Figure 4, including one example for each geomorphological unit and their various types. There are  
350 four groups based on their geomorphological characterization: (a) dunes; (b) highlands such as  
351 mountainous/hummocky and labyrinth terrains; (c) crater units and SEDs; and (d) plains. In Figure  
352 4 the extracted albedo from HLS is also present for comparative purposes.

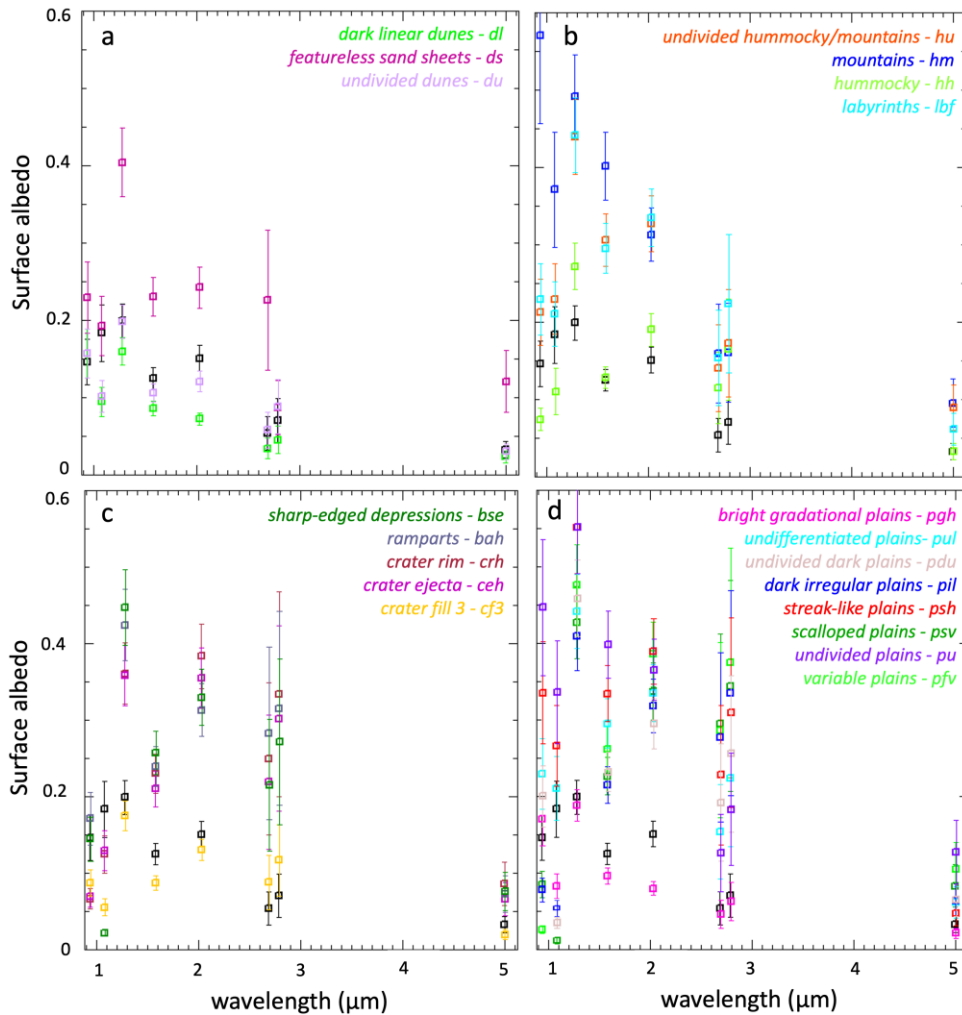
353 The overall albedo values of the dunes (Fig. 4a) at all wavelengths are among the lowest  
354 compared to the rest of the units, as demonstrated in previous studies (e.g., Soderblom et al., 2007;  
355 Barnes et al., 2008; Rodriguez et al., 2014; Bonnefoy et al., 2016; Solomonidou et al., 2016; 2018;  
356 Brossier et al., 2018). The featureless sand sheets (*ds*) present much brighter albedos than the other  
357 types of dunes, which we find correlated with their locations, as they appear mostly over 15°N and  
358 are completely absent from the equator. The dark linear dunes (*dl*) and the undivided dunes (*du*)  
359 have similar spectral behavior and albedo values within error bars at all wavelengths, except for  
360 the 2 μm window where the dark linear dunes have particularly low albedo, suggesting the  
361 presence of a constituent very absorbent at this wavelength. The lower albedo at all wavelengths  
362 for units closer to the equator is attributed to the transport and incorporation of dark material from  
363 the dunes due to aeolian transport processes (Malaska et al., 2016b; Lopes et al., 2016;  
364 Solomonidou et al., 2018; 2020a).

365 The highland terrains (Fig. 4b) present differences in their surface albedos, with the  
366 hummocky terrains (*hh*) having low albedo values, agreeing with the results in Solomonidou et al.  
367 (2018), and the mountainous terrains (*hm*) presenting significantly high albedo values, especially  
368 at the short wavelengths (0.94-2 μm). Interestingly, the undivided hummocky/mountainous  
369 terrains (*hu*) have albedo values in between the values of hummocky and mountainous terrains as  
370 shown in Fig. (4b). The labyrinth terrains (*lbf*) present relatively high surface albedos, with spectral  
371 similarities with the undifferentiated plains (*pul*) (Fig. 4d)

372 The albedos extracted from crater subunits (Fig. 4c) show that the crater fill 3 (*cf3*) is filled  
373 with the same material that is present in the dunes. The crater rim and crater ejecta show very  
374 similar spectral behavior and albedo values within error bars, something that was also shown for  
375 the Soi crater subunits in Solomonidou et al. (2020a). The albedos of the sharp-edged depressions  
376 (*bse*) and of their ramparts (*brh*) are intermediately bright with high values at the double window  
377 (2.69-2.79 μm) and the 5 μm window, similarly to the albedos extracted from VIMS data of three  
378 empty lake floors at 69°N-134°W in Solomonidou et al. (2020b). This study found that the material  
379 of the high-latitude empty lake floors is the same as the material of the raised ramparts that appear  
380 surrounding less than 10 SEDs of the north pole, suggesting that the ramparts are spectrally distinct  
381 from the surrounding plains.

382 Finally, the plains (Fig. 4d) present a great variety of different albedo values, with the new  
383 unit of gradational plains (*pgh*) having the lowest albedo of the plains units, marginally close to  
384 that of the dark linear dunes, following the dark linear dunes' drop in albedo from 1.59 to the 2  
385 μm window; a decrease that is not frequently observed in Titan's albedos. The dark irregular (*pil*),  
386 the undifferentiated (*pul*), the undivided dark (*pdu*), and the variable (*pfv*) plains present  
387 intermediate albedo values at the short wavelengths. The *pfv* is particularly bright at long  
388 wavelengths and the *pil* are very bright at the 2.69-2.79 μm double window. This brightness of  
389 Soi's *pfv* units at the 2.69-5 μm range was not observed in other locations of variable plains  
390 analyzed in Solomonidou et al. (2018) and seems compatible with the high latitude location of the  
391 Soi region variables that reach 50° N. The scalloped plains (*psv*) present intermediate to high  
392 albedo values at most wavelengths. The streak-like (*psh*) plains are very bright at all wavelengths,  
393 agreeing with the results in Solomonidou et al. (2018) and Lopes et al. (2016), while the newly

394 introduced undivided plains present high albedos at shorter wavelengths (0.94 – 2  $\mu\text{m}$ ), as well as  
 395 at 5  $\mu\text{m}$ .  
 396

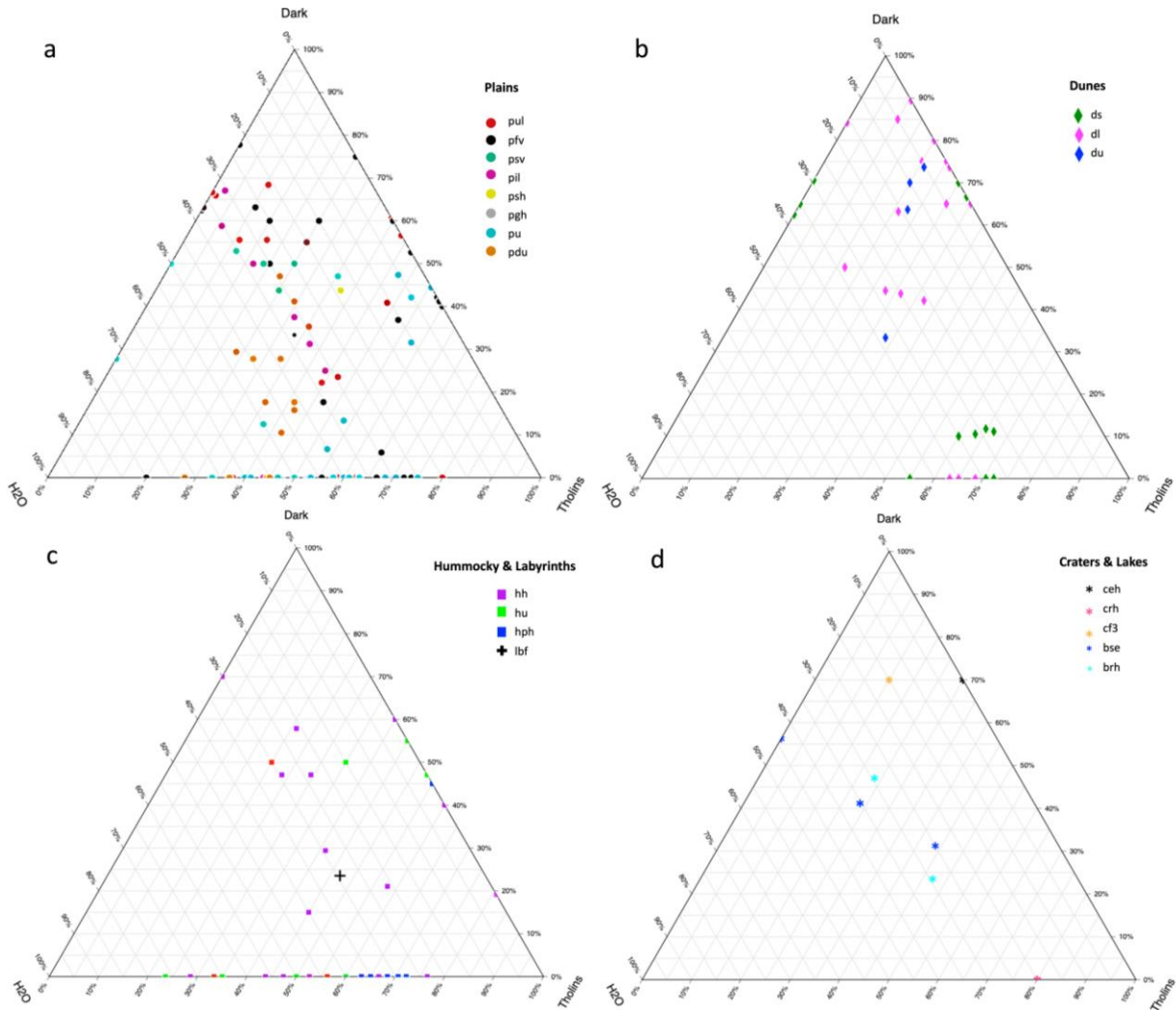


397  
 398 **Figure 4.** Examples of surface albedo weighted averages in the atmospheric windows as extracted  
 399 from VIMS data with RT for four different groups of units: (a) dunes; (b) hummocky/mountainous  
 400 and labyrinth; (c) impact crater units and sharp-edged depressions; and (d) plains. The Huygens  
 401 Landing Site (HLS) albedos (in black) are used as reference.

402 **3.3 Surface Mixtures**

403 The extracted albedos presented in the previous section are used in the mixing model to  
 404 provide linear mixture simulations that would fit the albedo data in the most optimal way, given  
 405 the available albedo points and the candidate Titan materials in the spectral database, and from the  
 406 perspective of what can be done in such a complex situation with limited available *in situ*  
 407 observations. Even if the fits between the mixture simulations and the albedo data are not perfect,  
 408 they provide insights into the surface composition of Titan’s top surface layer, which is still  
 409 unknown even after 13 years of Cassini exploration (e.g., Nixon et al., 2018; MacKenzie et al.,  
 410 2021). Table 3 includes the results from all 261 locations and Figure 5 presents ternary diagrams  
 411 for the composition of plains (a), dunes (b), hummocky terrains and labyrinths (c), and craters and

412 lakes (d). Examples of the mixture simulation results from representative units within the Soi crater  
 413 region can be found in Figure 6. The  $\chi^2$  values from the analyzed areas range from 0.24 to 3.48,  
 414 suggesting high correlation between the mixture simulations and the albedo data. From first read  
 415 of Figure 5 it seems that the majority of plains (5a) and hummocky and labyrinth terrains (5c) are  
 416 lacking the contribution of the dark organic material in their mixtures, something that as expected  
 417 the dunes (5b) have in abundance. The empty sharp-edged depressions, their surrounding ramparts,  
 418 and craters on the other hand seem to have a combination of all three constituents in their mixtures.  
 419



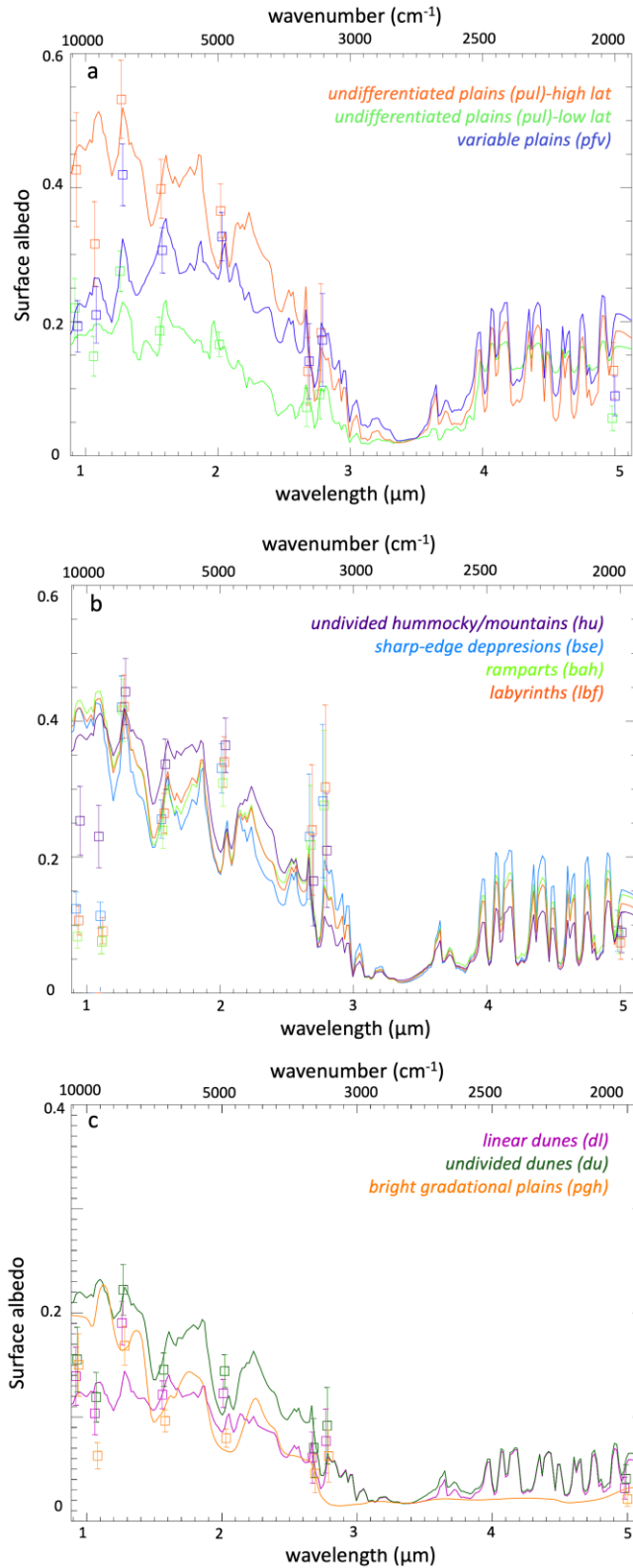
420  
 421 **Figure 5.** Ternary diagrams representing a composition from the three major constituents: H<sub>2</sub>O,  
 422 tholin-like constituent, and unknown dark constituent. (a) various types of plains; (b) various types  
 423 of dunes; (c) various types of hummocky terrains and labyrinths; (d) different parts of craters and  
 424 lake features. Detailed compositional constraints for each unit and their various locations can be  
 425 found in Table 3.

426  
 427 In our attempts to understand the chemical composition of Titan's surface as well as  
 428 possible, the code provides simulations of mixtures including at least four major constituents,  
 429 based on which we built our compositional map for the Soi crater region (see following section).  
 430 It was particularly difficult to reproduce in some cases the 0.94 and 1.08  $\mu\text{m}$  albedo values,

431 something that was previously found in Solomonidou et al. (2020a), when studying the  
432 composition of Titan's major impact craters. Furthermore, in Solomonidou et al. (2018) in a similar  
433 attempt to characterize the composition of the surface, fewer compounds were added from the  
434 library, which led to a worse fit especially for 0.94, 2.03, and 2.79 $\mu\text{m}$ . In this present study we  
435 have added more components in our simulation, increasing the number of component spectra  
436 available for potential matches in our library from 75 to 90, when taking into account the grain  
437 sizes. For the latter, the best fits are obtained using spectra from specific grain sizes for the different  
438 components since the albedo can be very dependent on the grain size, as shown in Figure 3. For  
439 the areas where their mixture includes tholins, the best fits are obtained using 30 $\mu\text{m}$  and 100 $\mu\text{m}$   
440 tholins. For CH<sub>4</sub> ice, the optimal grain size is 1000 $\mu\text{m}$ , while for H<sub>2</sub>O ice, it ranges from 10 $\mu\text{m}$  to  
441 50 $\mu\text{m}$ . Finally, among the various bitumens, the ones that provide the best fit with the extracted  
442 albedos are amorphous carbon at 200 $\mu\text{m}$  and 500 $\mu\text{m}$ , along with asphaltite.

443 In all 261 cases, we obtained matches within error bars in at least four out of the eight  
444 wavelengths. Such challenges in spectroscopic analyses for Titan have been faced by previous  
445 studies for both ground-based and Cassini-Huygens observations and measurements (VIMS,  
446 DISR) (Coustenis et al., 1995; Smith et al., 2005; Tomasko et al., 2005; Brown et al., 2006; Clark  
447 et al., 2010; Soderblom et al., 2007). Here, the matches that are more difficult to achieve are at the  
448 very short wavelengths, and for some cases the double window (2.69-2.79  $\mu\text{m}$ ), and the 5  $\mu\text{m}$   
449 window. The mismatch, especially at the shorter wavelengths, is indicative of the limitations set  
450 by the VIMS data, the modeling, and the variability of the material library compared to the  
451 expected complexity of Titan's surface. In contrast to previous surface composition simulation  
452 studies (Solomonidou et al., 2018; 2020a), here we are better able to match the 2  $\mu\text{m}$  and the 2.79  
453  $\mu\text{m}$  albedo data with mixtures of components. Furthermore, we have a match at 1.59  $\mu\text{m}$  in almost  
454 all 261 regions. In addition, some units present very low albedo values at short wavelengths and  
455 there is conspicuous absence of fit at 1.08 $\mu\text{m}$  compared to other units. Particularly intriguing are  
456 the SEDs, ramparts, and labyrinths, which exhibit markedly low albedos at short wavelengths and  
457 comparatively higher values at 2.03 and double-window wavelengths (Fig. 6b). This characteristic  
458 poses challenges for fitting all atmospheric windows, as the code uses materials within the current  
459 databases exhibiting absorption at short wavelengths while strongly reflecting light within the  
460 2.03-2.79 $\mu\text{m}$  range. Further work on the Cassini data, along with the advanced development of  
461 tools for their processing and additional data from future missions (e.g., Dragonfly) and  
462 observations (e.g., JWST), will help us better understand the reasons behind these mismatches and  
463 provide solutions for improved fits between the albedos and the simulated surface mixtures.

464 In the next section we discuss in detail the compositional behavior of each unit. In the next  
465 section we discuss in detail the compositional behavior of each unit.



466  
 467 **Figure 6.** Examples of inferred spectra based on modelled constituent mixtures of different units  
 468 in the Soi crater region. (a) Examples of an undifferentiated plain from over 30°N (*pul* -high lat),  
 469 from close to the equator (*pul* -low lat), and a variable plain (*pfv*). (b) Examples of a sharp-edged

470 depression (*bse*), of its surrounding rampart (*brh*), a labyrinth terrain (*lbf*), and an undivided  
471 hummocky terrain (*hu*). (c) Examples of a linear dune (*dl*), an undivided dune (*du*), and a  
472 gradational plain (*pgh*). The point symbols correspond to extracted surface albedos from locations  
473 shown in Figure 2 and others, and the full lines to the compositional simulations, which are  
474 produced by the code using the best fit attained between the simulated spectra and the albedos.  
475 The  $3\sigma$  error bars are shown on the simulations and are inferred by the code during the extraction  
476 of the surface albedos (detailed description of the  $3\sigma$  error bars can be found in section 3.1).

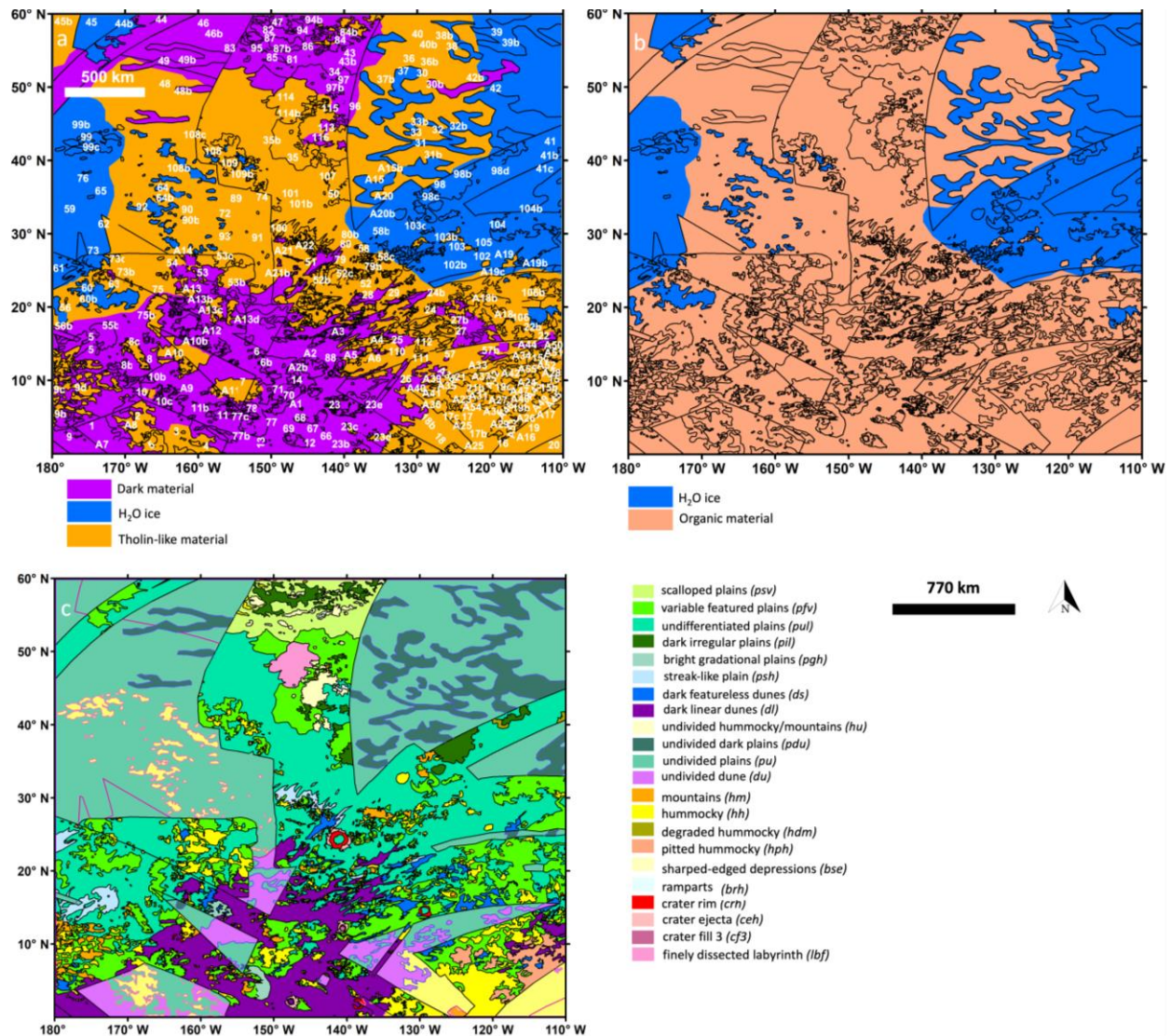
#### 477 3.4. Spectral Class Compositional Map

478 The 261 locations (Figure 2) we analyzed with VIMS from the Soi crater region showed  
479 that it is a diverse region in terms of compositional variety for the visible surface (Figure 7; Table  
480 3). Figure 7a shows the extrapolated compositional results of the selected regions of interest as  
481 shown in Figure 2 with contact lines distinguishing the boundaries of the various  
482 geomorphological units of which we discuss their composition in detail in this section. In Figure  
483 7b, we classified the extrapolated composition from Fig. 7a into ice and organic material; the latter  
484 includes the dark material and tholins. Figure 7c shows the results from mapping of the Soi crater  
485 region as presented in Schoenfeld et al. (2023). Here, we do not attempt to provide exact molecular  
486 composition, given the limitations of the VIMS data described earlier, rather we treat each material  
487 as a representative for possible compositions of the upper layer of the surface. Our radiative  
488 transfer code takes into account a large number of uncertainties and translates them into error bars  
489 as described in section 3.1 and shown in Figures 4 and 6. Given those caveats, we provide  
490 constraints on the chemical composition of the surface through the classification of spectral types  
491 of materials, focusing on the major constituent of the mixture and up to the 4<sup>th</sup> constituent in  
492 abundance (Table 3). As a reminder, these maps represent compositional constraints of mixtures  
493 that possibly make up the very thin veil (few microns) that cover the surface. The deeper layers  
494 (few cms) of the surface and their composition are being discussed later in this section (subsection  
495 3.5).

496 We will examine each unit separately, however one result that is common for all analyzed  
497 locations in the Soi crater region is that we found no indication for the presence of significant  
498 amounts of carbon dioxide ( $\text{CO}_2$ ), cyanoacetylene ( $\text{HC}_3\text{N}$ ), or ammonia ( $\text{NH}_3$ ) ices in the mixtures,  
499 to within our aforementioned uncertainties.

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 503 **Figure 7.** (a) Extrapolated composition map of the Soei crater region for the major constituents  
 504 from VIMS RT analysis and mixing model simulations with contact lines distinguishing the  
 505 boundaries of the various geomorphological units based on the boundaries drawn for the  
 506 geomorphological map in (c). The numbers represent the selections of regions of interest as  
 507 shown in Figure 2. The colored pixels are based on their compositional results for the major  
 508 constituent (blue for water-ice, magenta for dark organic material -a combination of bitumens and  
 509 amorphous carbon, orange for tholins). (b) Same as (a) with classification between ice (blue) and  
 510 organic (pink). (c) Geomorphological map for all SAR and non-SAR data (Schoenfeld et al., 2023)  
 511 at zero transparency (the map layer is fully opaque), same color scheme as the global  
 512 geomorphological map of Titan in Lopes et al. (2020).

513  
 514 All dune terrain units (*dl*, *du*, *ds*) have a primarily organic nature, but the different units  
 515 present differences in their secondary materials. The highland terrains (*hh*, *hm*, *hu*, *lbf*) lack a  
 516 characteristic major constituent among all their different units (Fig. 5c) and their nature depends  
 517 on their location. One common characteristic of all highland terrains is that they all appear to have  
 518 tholins in their mixtures (not as a major constituent) in significant amounts and that the presence

519 of CH<sub>4</sub>, as a tertiary or quaternary constituent, in their composition is stronger than in the dunes.  
520 The three crater units (*crh*, *ceh*, *cf3*) are primarily organic with the presence of water-ice only in  
521 the mixtures when the crater is located in regions dominated by plains (around the 30°N latitudinal  
522 zone), as shown in Solomonidou et al., (2020a). One such example is Soi crater. Furthermore, the  
523 composition of the empty sharp-edged depressions (*bse*) and their surrounding ramparts (*brh*) (Fig.  
524 5d) was found to be the same or very similar to those of the north polar empty lakes around 70°N  
525 discussed in Solomonidou et al. (2020b), which is a mixture of organics, water-ice, and simple  
526 organics. In Solomonidou et al. (2020b), it is noted that the emissivity of the northern raised  
527 ramparts points to a moderate-to-high contamination by organics. This emissivity is comparable  
528 to that of the northern empty basins. Combined with the VIMS results, this observation suggests  
529 that the ramparts and the empty lake floors, both located at the north pole, may share the same or  
530 similar composition. Here, as illustrated in Table 3 and discussed later in section 3.5, and similarly  
531 to the northern SEDs, the midlatitude empty SEDs are enriched in organic components.

532 The plains, in the same way as they present variable morphologies, present complex  
533 mixtures in their visible composition. The eight different units of plains are covered by different  
534 mixtures of materials. The recently introduced plain type (Schoenfeld et al., 2023), the gradational  
535 plains (*pgh*), is located close to the equator and below 20°N and is primarily organic in nature (dark  
536 material) and as shown in Fig. (4c) completely covered by dune materials. In contrast, the streak-  
537 like plains (*psh*) over 20°N do not include any dark material in their mixture and appear almost  
538 equally rich in water-ice and tholins. Similarly, the undivided dark plains (*pdu*), even though they  
539 were expected to be mostly abundant in the organic dark material due to their dark signature in  
540 VIMS, are instead relatively richer in water-ice, presenting some of the highest abundances in  
541 water-ice within the Soi crater region, along with the highland terrains. The undivided plains (*pu*)  
542 and the variable plains (*pfv*) are also covered by a mixture of organics and water-ice. The dark  
543 irregular plains (*pil*) and the scalloped plains (*psv*) are spectrally very similar, varying primarily in  
544 the amount of dark material present. Counterintuitively, the dark (in SAR) irregular plains, on  
545 average, have lower amounts of the dark material component than the scalloped plains. Previous  
546 analysis from a couple of scalloped plains (*psv*) from the region, which were analysed in  
547 Solomonidou et al. (2018) from older flybys (T25 and T94) than T97 (Table 2) and were found to  
548 be mainly abundant in water-ice, here are instead found to be abundant in the dark material (major)  
549 and water-ice (secondary). While our model uncertainties are significant, this may represent a  
550 change in the surface composition, which we hypothesize to be related to fluvial activity depositing  
551 a fresh overlying layer of dark material. Moreover, the dark irregular plains (*pil*) are mainly  
552 concentrated in latitudes higher than 30°N within the Soi crater region and were expected to be  
553 primarily rich in water-ice; however, even though water-ice is present in their mixtures, organic  
554 material seems to be the most abundant. Lastly, the undifferentiated plains (*pul*) seem to present a  
555 similar latitudinal dependence as shown in Solomonidou et al. (2018), with those in the 0-20°N  
556 zone being abundant in the dark material, while those in the higher latitudes being richer in water-  
557 ice (see Figure 7a;c). However, a large number of undifferentiated plains sample locations have  
558 tholins as the most abundant constituent, making these locations having the highest abundances in  
559 tholins. There is a significant amount of CH<sub>4</sub> in some cases reaching even 25% of the total mixture  
560 in some samples.

561 Detailed compositional constraints for each unit and their various locations can be found  
562 in Table 3. These are all suggestive compositional constraints and we acknowledge that they can  
563 be satisfied by other compositional solutions as well.

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### 3.5 Emissivity results

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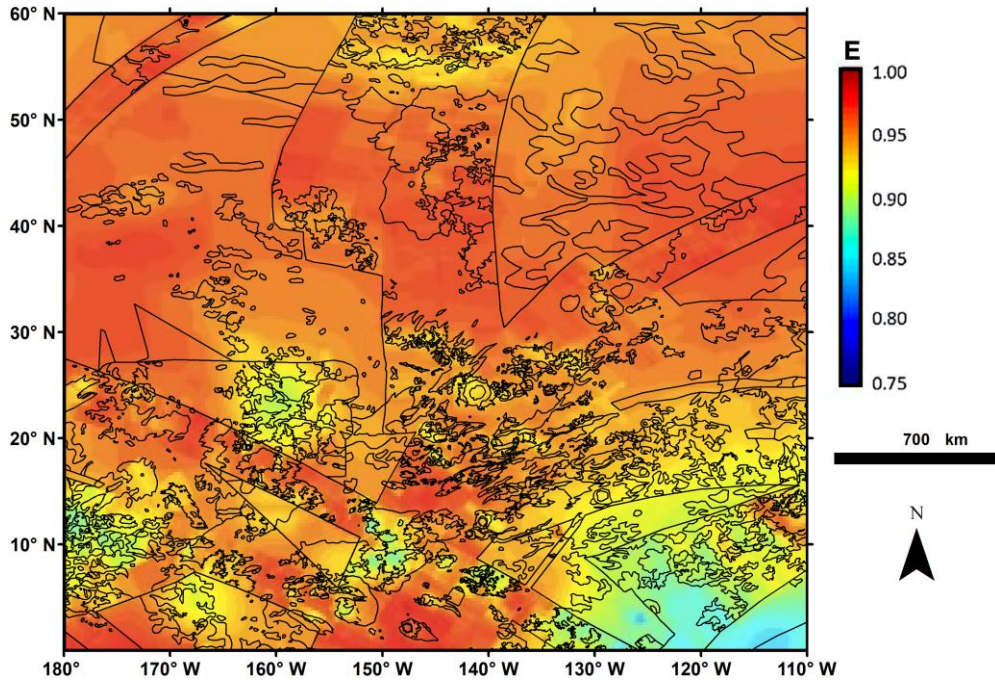
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As explained in Janssen et al. (2016) the presence of water-ice in the near subsurface is strongly indicated by the higher degree of volume scattering observed in radar-bright and low emissivity regions. Indeed, water-ice is highly transparent to microwaves, and therefore allows longer pathlengths which results in a higher probability for microwaves to encounter scatterers embedded in the subsurface. This in turn causes volume scattering, thus enhancing the radar cross-section and lowering the emissivity (Paillou et al., 2008; Janssen et al., 2016). A characteristic range of emissivity values for the different geomorphological units within the Soi crater region can be found in Table 1 in Schoenfeld et al. (2023) and the map of Figure 8. Though somewhat arbitrary, we interpret the units with values lower than 0.90 to be enriched in water-ice in their near subsurface (top decimeter of the regolith), and we interpret units with emissivity (E) values larger than 0.95 to be enriched in organic materials, and all values in between (E=0.90-0.95) to be consistent with a mixture of the two (Werynski et al., 2019; Malaska et al., 2020; Solomonidou et al., 2020a). The units that are more enriched in water-ice in their near subsurface (40 cm to 1 m) according to the emissivity values are the mountains, the hummocky terrains, and the undivided mountains/hummocky. The VIMS analysis agrees with the strong presence of water-ice in these units, which is always present in the mixtures of the top layer surface of these units; at few locations as major constituent (e.g., items 231-234 of Table 3) and except a very few regions of interest (e.g., items 192, 228 of Table 3) located near the equator which are completely coated with organic material (Table 3, items 191-249). However, a notable difference between the emissivity and VIMS/albedo results is the inconsistency in the major constituent of the mixtures at the southeast 'corner' of the Soi crater region of interest. Here, the emissivity data indicate a major water ice constituent (Fig. 8), while VIMS data suggest an organic one, specifically tholin-like material (Figs. 7a and 7b). The units that are more enriched in organic material according to emissivity are the dunes (*dl*, *ds*, *du*) with values ranging between 0.93 and 0.98. As shown in the previous section, the VIMS results of the top surface are in agreement with the organic nature of all types of dunes. Other units with strong organic nature according to emissivity include the undivided irregular plains (*pil*,  $E \geq 0.97$ ), the undifferentiated plains (*pul*,  $E \geq 0.97$ ), the undivided plains (*pu*,  $E \geq 0.96$ ), the undivided dark plains (*pdu*,  $E \geq 0.94$ ), the streak-like plains (*psh*,  $E \geq 0.95$ ), and the labyrinth terrains (*lbf*,  $E \geq 0.95$ ). The VIMS RT analysis of the top surface agrees with the organic appearance of *pil*, *pu*, and *pul* (depending on the latitude). However, the undivided dark plains and the streak-like plains appear more abundant in ice than organic material in the first few microns of their surface. It is important to note that the size and extent of the different features plays an important role in their emissivity measurements since small and thin patches of water-ice lying on an organic substrate may not be detected by radiometry. The rest of the units (*psv*, *pgh*, *du*, *cf3*, *ceh*, *ceh*, *brh*, and *bse*) have intermediate emissivity values suggesting a mixture of abundant icy and organic material with emissivity values ranging from 0.92 to 0.94. The VIMS analysis agrees with this icy and organic nature of the top surfaces of these units. Finally, the variable plains (*pfv*) present a large range of emissivity values (E=0.91-0.96) consistent with VIMS analysis suggesting a varying ice vs. organic nature for the unit depending on the location at all depths, from the thin  $\mu\text{m}$  veil covering the surface to  $10^2$ 's of centimeters deep in the surface.



606  
 607 **Figure 8.** Emissivity map of the Soi crater region with contact lines distinguishing the boundaries  
 608 of the various geomorphological units. Emissivity data from Janssen et al. (2016).

609

## 610 **4 Geologic History of the Soi crater region**

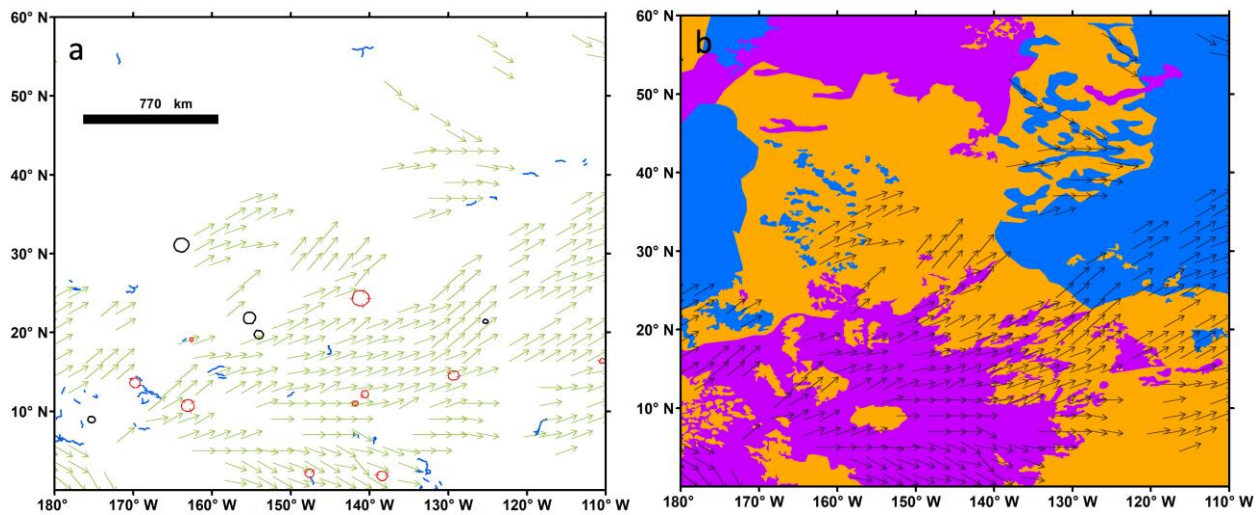
### 611 4.1 Surface Processes in Soi crater region

612 The Soi crater region is geomorphologically and compositionally variable, as shown in  
 613 Figure 7. In this section, we discuss the identified features from the various terrain types within  
 614 the region and we provide a geologic synthesis with respect to their chemical composition,  
 615 geomorphology, and potential geologic processes.

616 *Impact processes:* There are 10 impact craters identified within the Soi crater region (Wood  
 617 et al., 2010; Neish et al., 2015; Hedgpeeth et al., 2020; Schoenfeld et al., 2023). As also shown in  
 618 Figure 4c, where the differences in spectral responses between the ejecta and the floors are subtle,  
 619 the Soi crater region includes characteristic examples of how erosion affects the floors of the  
 620 craters by allowing dune material to intrude and deposit organic sand.

621 *Inferred Material Transport:* Wind and material transport models (Malaska et al., 2016b)  
 622 have helped distinguish different processes for the Soi crater region. Schoenfeld et al. (2023)  
 623 presented the sketch map of inferred material direction for the region, which we combined with  
 624 the map of chemical composition and present in Figure 9. The directions were based on alignments  
 625 and tapering morphologies of dunes, windstreaks and other terrains which enable the transport  
 626 direction to be inferred, for details see Malaska et al., (2016b). The map of chemical composition  
 627 correlates well with the flow path as shown in Figure 9b, with “extensions” of materials suggesting  
 628 that aeolian transport and subsequent deposition influences surface composition through delivery  
 629 of fine-grained saltating material (e.g., Schurmeier and Dombard, 2018). For example, in Figure  
 630 9b, extended “fingers” of dune materials (purple) are in the tholin-like plains zone (orange area).  
 631 While the inferred transport direction was determined from geomorphology (primarily by SAR),

632 it also appears to correlate to the compositional retrieval as well. This compositional analysis  
 633 further shows that the majority of the equatorial and low latitudes (0-20°N) are dominated by the  
 634 dark organic material that transition into an area more dominated by tholin-like materials in the  
 635 midlatitude. Similarly, mid to high-latitude zone with dark organic spectral components at 50-  
 636 60°N transitions to tholins in the midlatitudes (below 50°N) in a similar fashion. The areas rich in  
 637 water-ice appear over 20°N and they are suspected to be unrelated to material transport and  
 638 deposition and may be more connected to erosional processes. One possible mechanism that could  
 639 explain these observations would be a surface deposit of equatorially-derived mixed materials,  
 640 including water-ice and dark materials, which following deposition in the midlatitude plains either  
 641 have the coating removed (possibly through dissolution/leaching) to reveal a water ice-  
 642 enriched/tholin lag, or deposition with later coating from bright tholins from atmospheric airfall.  
 643



644 **Figure 9.** (a) Sketch map of inferred material transport direction (arrows) in the Soei crater region  
 645 after Malaska et al. (2016b), published in Figure 8 in Schoenfeld et al. (2023), with valleys and  
 646 channels (blue lines), craters (red), and putative craters (black). (b) Material transport direction on  
 647 top of the compositional map (color legend in Figure 7b).  
 648  
 649

650 *Fluvial, Aeolian, and Lacustrine Processes:* Two significant units found in the Soei crater  
 651 region, the bright gradational plains (*phg*) and the bright streak-like plains (*psh*), are proposed to  
 652 be two endmembers of the same type of fundamental deposit, reflecting either dominantly fluvial  
 653 or aeolian transport, respectively (Schoenfeld et al., 2023). These aeolian and fluvial origin  
 654 assumptions are based on geomorphological results from SAR data as presented in Schoenfeld et  
 655 al. (2013). According to the studies by Schoenfeld et al. (2023) and Malaska et al. (2016),  
 656 throughout all the mapping datasets the bright gradational plains and the bright streak-like plains  
 657 have both very similar signatures (bright), diffuse internal texture, and comparable microwave  
 658 emissivity. The elongated nature of *psh* with directions parallel to adjacent linear dunes suggests  
 659 aeolian origin for *psh*, while the *phg* units appear as broad plains originating from alluvial fans and  
 660 channels. The RT results from the analysis of VIMS data are consistent with these proposed  
 661 interpretations with regards to their origin (Sections 3.3, 3.4; Figure 4), since in the very top layer  
 662 of their surfaces, *phg* is one of the lowest in albedo, which could be consistent with fluvial origin  
 663 with a surface dampened by liquids. Meanwhile, *psh* is particularly bright at all wavelengths,  
 664 interpreted as an aeolian deposit with a lack of ponded liquids. As a result the high in albedo values

665 (bright) *psh* are associated with a dry surface, while the low in albedo values (dark) *pgl* with a wet  
666 surface. Radiometry data are inconclusive (*pgl*: 0.92-0.93 and *psh*: 0.94-0.96).

667 *Lacustrine Processes*: There are 60 features within the Soi crater region consistent with the  
668 morphology and size of the sharp-edged depressions (*bse*) of the north pole (Schoenfeld et al.,  
669 2023). In addition, two plains units, the scalloped plains (*psv*) (spectrally analysed in Solomonidou  
670 et al., 2018) and the dark irregular plains (*pil*), which are only been found in the midlatitude zone  
671 of Titan, are found adjacent to the SEDs (Schoenfeld et al., 2023).

672 As noted in Malaska et al. (2016a) and Lopes et al. (2020) both units play an important role  
673 in the definition of the mid-to-pole transitional zones and due to morphological and microwave  
674 emissivity measurements it is suggested that the *psv* is a unit with a thick organic layer much like  
675 the undifferentiated plains (Schoenfeld et al., 2021), with which the spectral analysis agrees,  
676 suggesting an organic nature with the dark material being dominant (Fig. 6). However,  
677 compositional analysis of the *psv* unit suggests that the second most abundant material in the  
678 optical surface is water-ice. We propose that this material is mostly organics at depth (consistent  
679 with microwave emissivity), but with an optical coating on the top consistent with spectral  
680 analysis, which is the opposite of what seems to occur at the Xanadu part of the Soi crater region.  
681 As discussed earlier, temporal analysis reveals an interesting temporal albedo change, with two  
682 particular *psv* becoming more abundant in dark material in 2014 (T97) than they were in 2007  
683 (T25) and 2013 (T94) (Solomonidou et al., 2016; 2018). All *pil* and *bse* share similar estimated  
684 compositions with *psv* having dark material and water-ice mainly in the mixtures of their top layer.

#### 685 4.2 Correlation of morphology and composition

686 We have analyzed the Soi crater region and identified various combinations of mixed  
687 materials in the top layer of the surfaces of the 22 geomorphological units, including organics,  
688 methane, and water-ice.

689 Our compositional mapping provides a glimpse into the compositional evolution of Titan.  
690 Similar to lower equatorial regions, we find abundant dark material to be the major constituent of  
691 a mid to high-latitude region ( $>40^{\circ}\text{N}$ , Fig. 7a). This is also the area where scalloped plains are  
692 ‘hosting’ the midlatitude SEDs and the dark irregular plains ( $40\text{-}60^{\circ}\text{N}$ ,  $140\text{-}170^{\circ}\text{W}$ ). In addition,  
693 methane-like (simple organics) spectral features are found widespread in the Soi crater region. The  
694 high emissivity results consistent with organic materials agree with the constraints put by the  
695 VIMS results except for two units: the dark irregular plains and the streak-like plains and the  
696 Xanadu region included in the Soi crater region, suggesting compositional differences in the  $\mu\text{m}$   
697 to cm layers.

698 In early VIMS studies, the major spectral “bright” units were found to generally correspond  
699 to mountains and elevated areas in radar (Barnes et al., 2007). Our results from the Soi crater  
700 region show that there is a significant amount of tholins that appears to be covering the top layers  
701 of the hummocky and mountainous terrains at the low latitudes (Fig. 7a), even though the vast  
702 majority of the low latitudes of the Soi region is covered with the dark organic material. Notably,  
703 another group of hummocky terrains is located in the midlatitudes ( $30\text{-}50^{\circ}\text{N}$ ) of the Soi crater  
704 region and consists mainly of water-ice with a secondary component of tholins. One common  
705 characteristic of all highland terrains is that they all appear to have tholins in their mixtures in  
706 significant amounts and/or significant amounts of  $\text{H}_2\text{O}$  ice. In addition, the percentage of methane-  
707 like materials (simple organics – aliphatic hydrocarbons) in top surfaces found at higher latitudes  
708 is larger than those found at lower latitudes (Table 3). Exposed crater rims show a mixture of only  
709 water-ice and tholins, suggesting that after the impact revealed water-ice (Crosta et al., 2021), it

710 was then coated in tholin, but not dark material. However, some highland areas that are exposed  
711 to significant fluxes of dune material also show dark material present, while those more protected  
712 appear to have less dark material present. In Solomonidou et al. (2018) the  
713 hummocky/mountainous units (all located near the equator and 210-245°W) were among the  
714 darkest, while in the Soi crater region they are the brightest in the short wavelengths suggesting  
715 some combination of materials that made them very bright at the short wavelength, which we  
716 attribute to increased tholin presence. The labyrinth terrains, even though they only appear in the  
717 Soi region at a specific location at around 50°N and represent only ~0.4% of the entire Soi crater  
718 region, spectrally look very similar to the ones analyzed in Solomonidou et al. (2018), namely  
719 Junction, Tleilax, and Richese and those in Malaska et al. (2020). The Soi region labyrinths are  
720 spectrally very similar to the undivided plain materials (*pu*), in both derived RT VIMS and  
721 microwave emissivity. They are both consistent with a surface of tholins and water-ice with bulk  
722 suggesting mostly organics.

723 Most craters with the Soi crater region appear to be almost entirely buried under organic  
724 material. The ones close to the equator lack any water-ice and are predominantly organic-rich,  
725 while the Soi crater rim and ejecta are rich with tholins, followed by water-ice, as also suggested  
726 in Solomonidou et al. (2020a).

727 The undivided dark plains (*pdu*) present some of the highest estimated percent abundances  
728 of water-ice within the Soi crater region, along with the hummocky/mountainous terrains. There  
729 are, however, three *pdu* high latitude exposures rich in the dark material mixed with water-ice.  
730 These differences of the optical surface between the different locations of the same unit suggest  
731 that either aeolian or fluvial activity removed part of the optically thin coat of the surface and  
732 revealed underlying, possibly wet material. Similarly, the absence of the dark organic material in  
733 the undivided plains (*pu*) could be attributed to aeolian and/or fluvial processes that have removed  
734 these materials from the visible surface.

735 Finally, most cases of the featureless sand sheets unit (*ds*), which only appear over 15°N,  
736 appear to be midway in composition between dune sands and midlatitude plains. That is, relative  
737 to the dunes, the sand sheet material has less dark material, but more tholin material. This is in  
738 contrast to the nature of the linear dunes (*dl*) of the Soi crater region, which are very consistent  
739 with having a dark organic composition, at least on the top surface. The featureless nature of *ds*  
740 and the fact that the tholins are often secondary suggests either an addition of tholin material to  
741 change the relative percentage, or a removal of dark materials. The generic results on the dune unit  
742 agree with the organic and less water ice nature of the VIMS ‘brown’ unit that corresponds to the  
743 dunes as per previous studies (Barnes et al., 2007; Soderblom et al., 2007).

744 Previous studies have highlighted a notable correlation between the chemical composition  
745 of the thin layer covering Titan's surface, as observed by VIMS (with a thickness on the order of  
746 micrometers), and latitude (Lopes et al., 2016; Malaska et al., 2016; Solomonidou et al., 2018;  
747 2020a). While there are instances where geomorphology and composition coincide, such as the  
748 distinct 'icy' undivided hummocky terrains (*hu*) within the expansive undivided plains (*pu*) of  
749 organic origin at midlatitudes, the influence of latitude, as well as aeolian and fluvial processes,  
750 appears to exert significant control over the surface material comprising the thin top layer.

#### 751 4.3 Interpreted geologic history

752 The Soi crater region has the typical geomorphology of most of Titan's surface. It contains  
753 plains, dunes, and mountainous terrains (Malaska et al., 2016a; Lopes et al., 2020; Schoenfeld et  
754 al., 2021; 2023) and a latitudinal dependence in chemical composition revealing almost complete

755 coverage of organic material in the equatorial regions and a surface expression of water-ice in the  
756 midlatitudes (Solomonidou et al., 2018; 2020b). However, at the higher latitudes a different  
757 geologic history is apparent for the Soi crater region.

758 The presence of dry lakes into the midlatitudes as low as 40°S supports the hypothesis that  
759 Titan had a wetter climate in the past (e.g., Moore et al., 2014). At these midlatitudes, scalloped  
760 plains and dark irregular plains have been identified (Schoenfeld et al., 2023) adjacent to the SEDs;  
761 this plain/lake northern area is one of the most interesting parts of the Soi region given that it is  
762 the first time that the dark organic material has been identified in abundance in a mid-to-high  
763 latitude area in the VIMS RT analysis (Fig. 7a).

764 Our results show that the areas around latitude 35°N are dominated by surface spectral  
765 responses typical of tholin materials, with ice-like materials and dark materials as minor  
766 components. Compared to the lower latitudes, there is an enhanced presence of aliphatic  
767 hydrocarbon-like materials (methane) in the midlatitudes, while in the higher latitudes, there is an  
768 even greater presence. Our compositional analysis is consistent with a gradation of aliphatic  
769 hydrocarbon materials being low at the equator, and increasing in relative percentage at higher  
770 latitudes (e.g., Mitchell, 2008; Rannou et al., 2006; Tokano et al., 2005; Faulk et al., 2017). The  
771 equatorial regions and high midlatitude plains units both contain elevated amounts of dark  
772 materials with a lower amount of tholin material when compared to the midlatitude plains units.

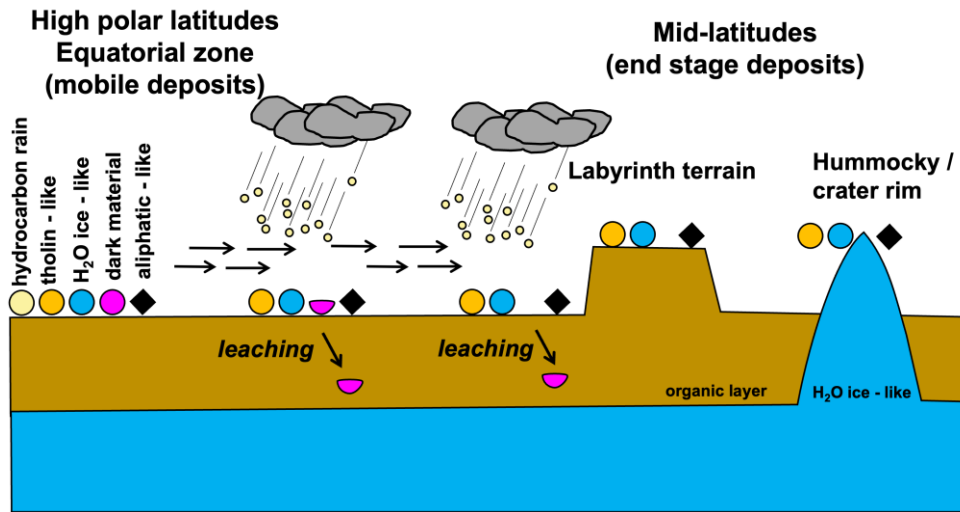
773 From arguments presented in Malaska et al. (2016b) on material transport, Titan's  
774 midlatitude regions appear to be areas fed from converging material coming from high latitudes  
775 towards the SE, and from equatorial areas towards the NE. This suggests that the midlatitude  
776 regions are composed of end stage of Titan windblown deposited materials that have since been  
777 subjected to rainfall and perhaps other aging processes. We find that materials at these convergent  
778 latitudes are spectrally similar to tholin-like materials and water ice-like materials. In order to  
779 convert dune materials and polar plains materials to midlatitude materials requires either removing  
780 the dark material component, or adding additional tholin components.

781 Addition could be due to density-selective transport, if we assume that all three materials  
782 have differing densities and/or material properties. For fluvially transported materials, large-scale  
783 storms (Faulk et al., 2017) have the potential to transport significant quantities of sediment as  
784 overbank deposits. If the tholins and water-ice materials are particularly buoyant compared to the  
785 dark materials, then floodplains should lack any significant dark material components. With  
786 greater spatial resolution, we would therefore expect floodplains to have a decreasing dark material  
787 component away from any given channel. Previous authors have noted the lack of channels in the  
788 midlatitude plains (Miller et al., 2021), although there may be effects that obscure the radar  
789 signature. In contrast, aeolian processes may transport all three types of sedimentary materials at  
790 any given time. To explain the dearth of dark materials at the convergent latitudes, we therefore  
791 require that such materials simply do not get deposited there. This could be due to either physical  
792 or chemical breakdown over short transport distances, or that the dark materials are denser than  
793 the other two sedimentary materials and get left behind due to density-selective transport. In this  
794 scenario, we postulate that dark materials may be denser and/or weaker, with both fluvial and  
795 aeolian mechanisms acting to sort Titan's different sedimentary materials. This would be  
796 analogous to size-selective transport on Earth, except with density playing the role in giving rise  
797 to uniquely separated deposits of sedimentary materials.

798 An alternative possibility is the removal of the dark organic component from the material  
799 deposited at the convergent latitudes. Tholin materials and water-ice materials are both predicted  
800 to be among the least soluble materials on Titan and would theoretically form a remnant lag



801 deposit, as more soluble materials, which could possibly include the dark materials, were leached  
 802 away into the subsurface by occasional rainfall. Leaching in geology corresponds to loss of soluble  
 803 substances from the top layer of the surface by percolating precipitation. Dark materials are present  
 804 in deposits to the N and in dune materials in the S in the Soi crater region. Since the dark materials  
 805 are present in presumably wetter polar deposits, we postulate that some of the dark materials may  
 806 be sourced there (possibly involving lakes or fluvial activity), while the midlatitudes create a  
 807 “sink” for these materials. We thus present an alternative compositional evolution cycle where  
 808 grains and materials coated in dark materials are delivered through aeolian transport into the  
 809 deposition belts and subjected to extensive leaching which dissolves the dark materials and allows  
 810 those dissolved materials to percolate into the deep subsurface, thus creating remnant optical  
 811 surface lag of insoluble materials rich in either water-ice or tholins (Fig. 10). This implies that  
 812 grains coated in dark materials are more recently formed and have not had their dark material  
 813 coatings removed. This also implies that dark material would be sourced at high latitudes (for  
 814 northern polar regions) and at low latitudes (for equatorial dunes).  
 815



816  
 817 **Figure 10.** Scheme showing midlatitude leaching of dark material from episodic rainfall on Titan.  
 818

819 Older exposed terrains thus should also be composed of tholins and water-ice materials, as  
 820 long as they are not receiving new dark material inputs. Thus, the mountains in the SE section of  
 821 Figure 7c, which is part of the extreme part of Northern Xanadu, appear to be ‘protected’ from  
 822 dark material deposition, or, most likely that removal process of the dark material have proceeded  
 823 quicker than overall deposition. Overall, we envision a scenario as shown in Figure 10, where  
 824 mobile materials contain dark material, that becomes leached, likely from episodic rainfall, as it  
 825 arrives to its end-stage destination in the midlatitudes. This scenario as pictured also is supported  
 826 by microwave emissivity data, which probes deeper. While end stage surface lag composed of  
 827 tholins coats labyrinth, mountain, and plains almost equally, the deeper probing microwave  
 828 emissivity can discriminate between hummocky and mountain materials composed of water-ice,  
 829 and scalloped/undifferentiated plains and labyrinths composed of organic materials.  
 830

## 831 5 Conclusion

832 The Soi crater region is an important Titan region as it represents the transition between  
833 the equatorial, the midlatitudes, and the high-altitudes of the northern hemisphere of Titan. Our  
834 analysis developed a working hypothesis for the formation and evolution of the Soi crater region  
835 through the combination of the geomorphological mapping performed by Schoenfeld et al. (2023)  
836 and compositional mapping and radiative transfer analysis performed here. Our work suggests  
837 propable relationships between the dunes (source), scalloped plains (source), and undifferentiated  
838 plains (sink) and brings together and explains the differences in nature of the top layers of the  
839 surface from infrared spectra and microwave emissivity measurements. It also infers the geological  
840 processes and relationships responsible for their formation and evolution. We suggest that the dark  
841 material is a mobile unit that indicates “young” terrains and compositions, while tholin/water-ice  
842 mixtures that dominate areas around latitude 35°N show a material that is older and closer to end  
843 stage aeolian plain deposits. This suggests that Titan’s compositional evolution cycle includes  
844 aeolian transport and leaching. These results provide a better understanding of the geologic  
845 processes that govern Titan’s surface and will help enhance the science return of future missions  
846 such as Dragonfly, and other mission concepts (e.g., Tobie et al., 2014; Lorenz et al., 2021; Barnes  
847 et al., 2021; Sulaiman et al., 2021; Rodriguez et al., 2022).

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862

## 863 Open Research

864 All *Cassini* data used in this article can be accessed in the Planetary Data Systems (PDS), PDS  
865 Image Atlas ( [for  
866  \[for  
867 VIMS and  \\[RADAR. The detailed product IDs for VIMS can be found in Table 2. The  
868 spectral library databases can be accessed here: <http://ghosst.osug.fr>. Full descriptions of the  
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873\\]\\(https://pds-imaging.jpl.nasa.gov/search/?fq=ATLAS\\_MISSION\\_NAME%3Acassini&fq=TARGET%3Atitan&fq=-ATLAS\\_THUMBNAIL\\_URL%3Abrwsnotavail.jpg&fq=ATLAS\\_INSTRUMENT\\_NAME%3Aradar&q=%3A\\*\\)\]\(https://pds-imaging.jpl.nasa.gov/search/?fq=-ATLAS\_THUMBNAIL\_URL%3Abrwsnotavail.jpg&fq=ATLAS\_MISSION\_NAME%3Acassini&fq=TARGET%3Atitan&q=%3A\*\)](https://pds-imaging.jpl.nasa.gov/search/?fq=-ATLAS_THUMBNAIL_URL%3Abrwsnotavail.jpg&fq=ATLAS_MISSION_NAME%3Acassini&fq=ATLAS_INSTRUMENT_NAME%3Avims&fq=TARGET%3Atitan&q=%3A*)

874 radiative transfer model are provided by Hirtzig et al., (2013)  
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876 Imaging and Analysis software ([https://www.l3harrisgeospatial.com/Software-](https://www.l3harrisgeospatial.com/Software-Technology/ENVI)  
877 [Technology/ENVI](https://www.l3harrisgeospatial.com/Software-Technology/ENVI)) and the Interactive Data Language (IDL), both provided by L3Harris  
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879  
880

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1237 **Appendix**

1238

1239 **Table 3.** Compositional constraints of the various units (261 locations) within the Soi crater region.  
1240 The various locations are shown in Figure 4. The mixtures are given by percentages of different  
1241 constituents (H<sub>2</sub>O, CH<sub>4</sub>, tholins, and dark organic material). HC<sub>3</sub>N, CO<sub>2</sub>, NH<sub>3</sub> ices were not  
1242 detected in these locations. Spectra in full resolution for all presented constituents can be found in  
1243 Figure 3.

Items	Location	Unit	Dark	H <sub>2</sub> O ice	Tholins %	CH <sub>4</sub> %
1.	8	<i>pul</i>	40	10	45	5
2.	8b	<i>pul</i>	60	-	40	-
3.	14	<i>pul</i>	60	-	45	-
4.	24b	<i>pul</i>	20	30	40	10
5.	29	<i>pul</i>	-	40	40	20
6.	41	<i>pul</i>	-	50	25	25
7.	44	<i>pul</i>	50	30	10	10
8.	52	<i>pul</i>	-	20	80	-
9.	53b	<i>pul</i>	-	25	60	15
10.	55b	<i>pul</i>	35	15	30	20
11.	56	<i>pul</i>	-	25	60	15
12.	58b	<i>pul</i>	-	45	35	10
13.	63	<i>pul</i>	-	50	40	10
14.	73c	<i>pul</i>	20	25	40	15
15.	79	<i>pul</i>	-	25	60	15
16.	80b	<i>pul</i>	-	40	60	-
17.	98b	<i>pul</i>	-	45	35	20
18.	101	<i>pul</i>	-	45	50	5
19.	101b	<i>pul</i>	-	45	50	5
20.	102b	<i>pul</i>	-	50	45	5
21.	105	<i>pul</i>	-	40	55	5
22.	106	<i>pul</i>	-	30	65	5
23.	108c	<i>pul</i>	-	30	50	20
24.	A3	<i>pul</i>	50	25	15	10
25.	A4	<i>pul</i>	65	20	10	5
26.	A6	<i>pul</i>	60	35	-	5
27.	A13	<i>pul</i>	60	30	-	10
28.	A13c	<i>pul</i>	60	30	-	10
29.	A18b	<i>pul</i>	-	35	50	15
30.	A20	<i>pul</i>	-	50	30	20
31.	A22	<i>pul</i>	-	30	50	20
32.	6b	<i>pfv</i>	60	15	25	-
33.	8c	<i>pfv</i>	50	-	45	5
34.	9c	<i>pfv</i>	40	-	55	5
35.	10	<i>pfv</i>	35	10	50	5
36.	10c	<i>pfv</i>	60	-	40	-
37.	11b	<i>pfv</i>	60	25	15	-
38.	12	<i>pfv</i>	60	-	40	-
39.	21	<i>pfv</i>	-	25	65	10
40.	22b	<i>pfv</i>	35	-	50	10
41.	23	<i>pfv</i>	70	20	-	10
42.	27b	<i>pfv</i>	40	-	60	-
43.	34	<i>pfv</i>	45	30	10	15
44.	35	<i>pfv</i>	5	25	55	15
45.	35b	<i>pfv</i>	5	25	55	15
46.	44b	<i>pfv</i>	15	40	30	15
47.	53c	<i>pfv</i>	15	30	40	15
48.	56b	<i>pfv</i>	-	45	40	15
49.	58c	<i>pfv</i>	-	45	35	10
50.	60	<i>pfv</i>	-	55	45	-
51.	60b	<i>pfv</i>	-	55	45	-
52.	67	<i>pfv</i>	75	-	25	-
53.	70	<i>pfv</i>	60	25	10	5
54.	73	<i>pfv</i>	-	50	50	-
55.	75	<i>pfv</i>	-	40	60	-
56.	75b	<i>pfv</i>	-	40	60	-

57.	77b	<i>pfv</i>	50	30	20	-
58.	79b	<i>pfv</i>	-	25	60	15
59.	97	<i>pfv</i>	50	30	-	20
60.	104	<i>pfv</i>	-	60	35	5
61.	107	<i>pfv</i>	-	40	50	10
62.	108	<i>pfv</i>	-	40	40	20
63.	109b	<i>pfv</i>	-	40	40	20
64.	110	<i>pfv</i>	-	35	60	5
65.	A2b	<i>pfv</i>	60	35	-	5
66.	A13b	<i>pfv</i>	-	30	60	10
67.	A18	<i>pfv</i>	35	-	50	15
68.	A19b	<i>pfv</i>	-	55	45	-
69.	A36	<i>pfv</i>	-	25	70	5
70.	A41	<i>pfv</i>	-	30	65	5
71.	A53	<i>pfv</i>	-	30	65	5
72.	43	<i>psv</i>	45	30	10	15
73.	43b	<i>psv</i>	45	30	10	15
74.	47	<i>psv</i>	40	25	15	20
75.	81	<i>psv</i>	35	25	20	20
76.	87	<i>psv</i>	40	20	20	20
77.	87b	<i>psv</i>	40	25	20	15
78.	50	<i>pil</i>	-	25	55	20
79.	82	<i>pil</i>	45	30	15	10
80.	84b	<i>pil</i>	20	25	35	20
81.	94	<i>pil</i>	30	25	25	20
82.	94b	<i>pil</i>	25	25	30	20
83.	95	<i>pil</i>	55	25	-	20
84.	96	<i>pil</i>	50	30	5	15
85.	97b	<i>pil</i>	50	30	5	15
86.	98	<i>pil</i>	-	45	35	20
87.	98c	<i>pil</i>	-	45	35	20
88.	55	<i>psh</i>	35	15	30	20
89.	61	<i>psh</i>	-	50	50	-
90.	80	<i>psh</i>	-	40	60	-
91.	100	<i>psh</i>	-	35	55	10
92.	77	<i>pgh</i>	55	20	25	-
93.	78	<i>pgh</i>	55	20	25	-
94.	A10b	<i>pgh</i>	55	20	25	-
95.	4	<i>pu</i>	40	5	50	5
96.	5	<i>pu</i>	30	10	55	5
97.	7	<i>pu</i>	45	5	45	5
98.	30b	<i>pu</i>	5	30	40	25
99.	31b	<i>pu</i>	5	30	40	25
100.	33	<i>pu</i>	10	25	40	25
101.	36	<i>pu</i>	-	30	45	25
102.	36b	<i>pu</i>	-	30	45	25
103.	39b	<i>pu</i>	25	65	-	10
104.	40	<i>pu</i>	-	40	45	15
105.	40b	<i>pu</i>	-	40	45	15
106.	41c	<i>pu</i>	-	45	30	25
107.	42	<i>pu</i>	35	35	-	30
108.	45	<i>pu</i>	10	40	30	20
109.	45b	<i>pu</i>	-	20	60	20
110.	46	<i>pu</i>	30	25	30	15
111.	46b	<i>pu</i>	40	15	30	15
112.	48	<i>pu</i>	-	20	60	20
113.	57	<i>pu</i>	-	35	60	5

114.	59	<i>pu</i>	-	45	40	15
115.	62	<i>pu</i>	-	35	40	25
116.	64	<i>pu</i>	-	35	40	25
117.	65	<i>pu</i>	-	50	35	15
118.	72	<i>pu</i>	-	35	55	10
119.	74	<i>pu</i>	-	40	55	5
120.	76	<i>pu</i>	-	40	35	25
121.	89	<i>pu</i>	-	40	55	5
122.	90	<i>pu</i>	-	50	50	-
123.	90b	<i>pu</i>	-	40	55	5
124.	91	<i>pu</i>	-	25	60	15
125.	93	<i>pu</i>	-	35	60	5
126.	99b	<i>pu</i>	-	60	30	10
127.	106b	<i>pu</i>	-	30	65	5
128.	111	<i>pu</i>	-	35	60	5
129.	A10	<i>pu</i>	40	-	50	10
130.	30	<b><i>pdu</i></b>	25	40	25	10
131.	31	<i>pdu</i>	25	35	30	10
132.	32	<i>pdu</i>	15	35	35	15
133.	32b	<i>pdu</i>	15	40	30	15
134.	33b	<i>pdu</i>	15	40	30	15
135.	37	<i>pdu</i>	15	40	40	5
136.	37b	<i>pdu</i>	10	45	40	5
137.	38	<i>pdu</i>	25	40	20	15
138.	38b	<i>pdu</i>	25	40	20	15
139.	39	<i>pdu</i>	-	65	25	10
140.	42b	<i>pdu</i>	40	25	20	15
141.	48b	<i>pdu</i>	40	25	20	15
142.	49	<i>pdu</i>	35	25	25	15
143.	49b	<i>pdu</i>	30	25	30	15
144.	104b	<i>pdu</i>	-	60	35	5
145.	A15	<i>pdu</i>	-	50	40	10
146.	A15b	<i>pdu</i>	-	50	40	10
147.	A19c	<i>pdu</i>	-	55	45	-
148.	9b	<b><i>ds</i></b>	60	25	-	15
149.	19c	<i>ds</i>	60	25	-	15
150.	21b	<i>ds</i>	10	20	60	10
151.	22	<i>ds</i>	10	20	55	15
152.	24	<i>ds</i>	50	30	-	20
153.	25	<i>ds</i>	60	25	-	15
154.	27	<i>ds</i>	65	35	-	-
155.	51	<i>ds</i>	60	-	30	10
156.	54	<i>ds</i>	70	-	30	-
157.	A5	<i>ds</i>	10	30	60	-
158.	A19	<i>ds</i>	-	45	55	-
159.	A31	<i>ds</i>	-	25	60	15
160.	A39	<i>ds</i>	-	25	65	10
161.	A40	<i>ds</i>	10	25	60	5
162.	A47	<i>ds</i>	-	35	60	5
163.	A48	<i>ds</i>	-	35	65	-
164.	A49	<i>ds</i>	-	35	65	-
165.	6	<b><i>dl</i></b>	65	5	30	-
166.	9	<i>dl</i>	75	5	20	-
167.	10b	<i>dl</i>	80	-	20	-
168.	11	<i>dl</i>	85	5	10	-
169.	13	<i>dl</i>	75	-	25	-
170.	15	<i>dl</i>	75	-	25	-

171.	23b	<i>dl</i>	65	-	35	-
172.	28	<i>dl</i>	45	30	15	10
173.	66	<i>dl</i>	75	-	25	-
174.	A1	<i>dl</i>	85	-	10	5
175.	A2	<i>dl</i>	80	15	-	5
176.	A9	<i>dl</i>	70	-	25	5
177.	A12	<i>dl</i>	60	15	20	5
178.	A21b	<i>dl</i>	35	20	25	20
179.	A27	<i>dl</i>	40	25	25	10
180.	A28	<i>dl</i>	40	20	35	5
181.	A34	<i>dl</i>	-	35	60	5
182.	A44	<i>dl</i>	-	30	65	5
183.	A46	<i>dl</i>	-	30	65	5
184.	A52	<i>dl</i>	-	35	65	-
185.	1	<b><i>du</i></b>	70	5	20	5
186.	23e	<i>du</i>	65	-	30	5
187.	26	<i>du</i>	60	-	35	5
188.	57b	<i>du</i>	60	-	30	10
189.	A7	<i>du</i>	70	10	20	-
190.	A13d	<i>du</i>	70	15	25	-
191.	9d	<b><i>hm</i></b>	50	30	20	-
192.	19b	<i>hm</i>	40	-	45	15
193.	41b	<i>hm</i>	-	50	25	25
194.	58	<i>hm</i>	-	35	45	10
195.	77c	<i>hm</i>	50	30	20	-
196.	103b	<i>hm</i>	-	45	50	5
197.	15c	<b><i>hh</i></b>	45	-	55	-
198.	16	<i>hh</i>	-	40	60	-
199.	17	<i>hh</i>	-	25	60	15
200.	17b	<i>hh</i>	-	25	60	15
201.	17c	<i>hh</i>	-	20	65	15
202.	23d	<i>hh</i>	40	-	60	-
203.	53	<i>hh</i>	60	-	40	-
204.	68	<i>hh</i>	55	20	20	5
205.	71	<i>hh</i>	70	30	-	-
206.	73b	<i>hh</i>	40	20	25	15
207.	83	<i>hh</i>	40	25	20	15
208.	102	<i>hh</i>	-	45	50	5
209.	103	<i>hh</i>	-	50	45	5
210.	109	<i>hh</i>	-	50	20	30
211.	A11	<i>hh</i>	20	20	55	5
212.	A14	<i>hh</i>	15	40	45	-
213.	A32	<i>hh</i>	-	25	65	10
214.	A33	<i>hh</i>	-	25	60	15
215.	A20b	<i>hh</i>	-	45	35	20
216.	A21	<i>hh</i>	25	25	35	15
217.	A24	<i>hh</i>	-	25	65	10
218.	A25	<i>hh</i>	-	25	60	15
219.	A37	<i>hh</i>	-	30	65	5
220.	A38	<i>hh</i>	-	30	65	5
221.	A50	<i>hh</i>	-	40	60	-
222.	A51	<i>hh</i>	-	30	60	10
223.	A54	<i>hh</i>	-	30	65	5
224.	A55	<i>hh</i>	-	35	60	5
225.	2	<b><i>hu</i></b>	10	25	60	5
226.	3	<i>hu</i>	50	15	35	-
227.	18	<i>hu</i>	40	-	45	15

228.	18b	<i>hu</i>	40	-	45	15
229.	19	<i>hu</i>	-	25	65	10
230.	20	<i>hu</i>	40	-	45	15
231.	64b	<i>hu</i>	-	65	35	-
232.	92	<i>hu</i>	-	65	35	-
233.	99	<i>hu</i>	-	65	20	15
234.	99c	<i>hu</i>	-	65	20	15
235.	108b	<i>hu</i>	-	40	40	20
236.	A8	<i>hu</i>	55	-	45	-
237.	A16	<i>hu</i>	-	40	60	-
238.	A17	<i>hu</i>	-	35	65	-
239.	15b	<b><i>hph</i></b>	45	-	55	-
240.	A23	<i>hph</i>	-	25	60	15
241.	A26	<i>hph</i>	-	30	65	5
242.	A29	<i>hph</i>	-	25	65	10
243.	A30	<i>hph</i>	-	30	65	5
244.	A35	<i>hph</i>	-	30	65	5
245.	A42	<i>hph</i>	-	35	60	5
246.	A43	<i>hph</i>	-	35	60	5
247.	A45	<i>hph</i>	-	35	65	-
248.	114	<b><i>lbf</i></b>	20	25	40	15
249.	114b	<i>lbf</i>	20	25	40	15
250.	23c	<b><i>ceh</i></b>	70	-	30	-
251.	52b	<i>ceh</i>		20	80	-
252.	69	<i>ceh</i>	70	-	30	-
253.	52c	<b><i>crh</i></b>		20	80	-
254.	112	<i>crh</i>	-	20	80	-
255.	88	<b><i>cf3</i></b>	70	15	15	-
256.	84	<b><i>bse</i></b>	45	35	-	20
257.	85	<i>bse</i>	35	30	20	15
258.	86	<i>bse</i>	35	30	20	15
259.	113	<i>bse</i>	25	20	35	20
260.	115	<b><i>brh</i></b>	20	25	40	15
261.	116	<i>brh</i>	40	25	20	15

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## Detailed chemical composition analysis of the Soi crater region on Titan

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### Highlights:

- Titan’s compositional evolution cycle includes aeolian transport and leaching.
- Areas around latitude 35°N are dominated by tholin and ice-like spectral signatures
- The midlatitudes are composed of end-stage materials that were subjected to rainfall.
- Empty lakes at the midlatitudes have same composition as the northern empty lakes.

## 30 **Abstract**

31 The Soi crater region (0° to 60°N, 180°W to -110°W), which includes the well-preserved Soi crater  
32 in its center, spans a region from Titan’s aeolian-dominated equatorial regions to fluvially-  
33 dominated high northern latitudes. This provides a rich diversity of landscapes, one that is also  
34 representative of the diversity encountered across Titan. Schoenfeld et al. (2023) mapped this  
35 region at 1:800,000 scale and produced a geomorphological map showing that the area consists of  
36 22 types of geomorphological units. The Visual and Infrared Mapping Spectrometer (VIMS)  
37 coverage of the region enabled the detailed analysis of spectra of 261 different locations using a  
38 radiative transfer technique and a mixing model, yielding compositional constraints on Titan’s  
39 optical surface layer. Additional constraints on composition on the near-surface substrate were  
40 obtained from microwave emissivity. We have derived combinations of top surface materials  
41 between dark materials, tholins, water-ice, and methane suggesting that dark mobile organic  
42 material at equatorial and high latitudes indicates “young” terrains and compositions, while  
43 tholin/water-ice mixtures that dominate areas around latitude 35°N show a material that is older  
44 plains deposits that we interpret to be the end stage of aeolian and fluvial transport and deposition.  
45 We found no spectral evidence of CO<sub>2</sub>, HC<sub>3</sub>N, and NH<sub>3</sub> ice. We use the stratigraphic relations  
46 between the various mapping units and the relation between the geomorphology and the  
47 composition of the surface layers to build hypotheses on the origin and evolution of the regional  
48 geology. We suggest that sedimentary deposits, likely aeolian, are dominant in the region with  
49 fluvial activity and leaching changing the nature of the top surfaces of the midlatitude areas of the  
50 Soi crater region.

## 51 **1 Introduction**

52 The surface of Saturn’s moon Titan has been revealed by the Cassini-Huygens spacecraft  
53 to be geologically complex with both exogenic and putative endogenic processes modifying its  
54 appearance. Titan’s dense atmosphere and active methane cycle has enabled aeolian, fluvial,  
55 pluvial, and lacustrine processes, causing erosion and deposition. Few impact craters are seen,  
56 attesting that the surface is geologically young (e.g., Wood et al., 2010; Hedgepeth et al., 2020).  
57 Tectonism and possibly cryovolcanism have also contributed to surface modification (Jaumann et  
58 al., 2009; Mitri et al., 2008, 2010; Radebaugh et al., 2007; Lopes et al., 2013; 2019; Wall et al.,  
59 2009; Nelson et al., 2009; Solomonidou et al., 2013; 2016; Sohl et al., 2014; Wood and Radebaugh,  
60 2020). The rich variety of geologic features on Titan and how the processes have dominated  
61 different latitudes have been discussed in previous works. For example, lakes and seas are present  
62 at high latitudes (e.g., Stofan et al., 2007; Bratsolis et al., 2012; Birch et al., 2016), while dunes of  
63 organic materials are concentrated at low latitudes (Lorenz et al., 2006; Radebaugh et al., 2008;  
64 Lopes et al., 2010; Rodriguez et al., 2014). Fluvial channel networks are present across large areas  
65 of the surface (Jaumann et al., 2008; Malaska et al., 2011; Langhans et al., 2012; Burr et al., 2013;  
66 Radebaugh et al., 2016; Miller et al., 2021), with a rich diversity in morphology (Burr et al., 2013;  
67 Miller et al., 2021), and are both liquid-filled (Poggiali et al., 2016) and dry. The mountainous and  
68 hummocky units represent remnants of an older crust, making them the oldest exposed unit on  
69 Titan, and they mostly appear in the equatorial zones and small areas all over the globe (Williams  
70 et al., 2011; Lopes et al., 2020a; Malaska et al., 2016a; 2020; Schoenfeld et al., 2021). Organic  
71 materials, produced by high-altitude photochemistry of methane and nitrogen in Titan’s  
72 atmosphere, cover much of Titan’s surface (Wilson and Atreya, 2004; Lavvas et al., 2008;  
73 Krasnopolsky, 2009; Clark et al., 2010; Solomonidou et al., 2018; 2020a). The buildup of these  
74 organic materials is evidenced by large standing dissected plateaux elevated by hundreds of meters

75 (Malaska et al., 2020). The midlatitudes of Titan are dominated by undifferentiated plains (Lopes  
76 et al., 2016; 2019; 2020) which are interpreted as being sedimentary in nature and likely formed  
77 by aeolian processes (Malaska et al., 2016b). Titan’s latitudinal dependence for composition of the  
78 upper surface layer (Solomonidou et al., 2018), as well as patterns of wind deposition (Malaska et  
79 al., 2016b), show that, for both hemispheres, winds may transport material from both equatorial  
80 regions and high latitudes towards a zone at  $\sim 35^\circ$ . That zone, at the midlatitudes may represent a  
81 ‘sink’, where materials are deposited as undifferentiated plains (Lopes et al., 2016; Malaska et al.,  
82 2016b; Solomonidou et al., 2020a).

83 The Soi crater region is scientifically valuable as it straddles the equatorial, midlatitude,  
84 and northern regions of Titan. The present study on the composition complements the  
85 geomorphological study of Schoenfeld et al. (2023). Our compositional map for this region is  
86 created using a radiative transfer code with Visual and Infrared Mapping Spectrometer (VIMS)  
87 data that help estimate the haze contribution to the data and extract surface information that are  
88 later matched to surface component mixture simulations (Hirtzig et al., 2013; Bonnefoy et al.,  
89 2016; Solomonidou et al., 2014; 2018; 2020a;b). The goal of this paper is to bring constraints on  
90 the formation and evolution of the selected area through the combination of the geomorphological  
91 and compositional maps of the Soi crater region. The maps will help reveal the types and extent  
92 of the geomorphologic units and the differences in nature of the top layers of the surface, and to  
93 infer the geological processes responsible for their formation and evolution. Our compositional  
94 mapping follows the methods described in Solomonidou et al. (2014; 2018; 2020a;b). Our efforts  
95 here are part of a global compositional mapping project that is currently in progress (Solomonidou  
96 et al., 2022), attempting to improve our knowledge of Titan’s complex systems.

97

## 98 **2 Geologic Setting**

99 The Soi crater region was defined in Schoenfeld et al. (2023) as the area spanning from  
100 longitude  $180^\circ$  W to  $110^\circ$  W and from latitude 0 to  $60^\circ$ N and the area contained in this region  
101 amounts to  $\sim 8 \times 10^6$  km<sup>2</sup> ( $\sim 9.7\%$  of Titan’s surface). This region is geomorphologically mapped in  
102 detail and presented in the same article. For the production of the map by Schoenfeld et al. (2023)  
103  $\sim 5.6\%$  of the total surface area was mapped by using high resolution Synthetic Aperture Radar  
104 (SAR) data and the rest of the area was covered by non-SAR data (microwave emissivity, Imaging  
105 Science Subsystem -ISS, and VIMS), and mapped at lower resolution. For VIMS and the  
106 compositional mapping efforts, the area that was covered with data compatible and adequate to  
107 our radiative transfer modeling (detailed in section 3) spanned approximately  $5.4 \times 10^6$  km<sup>2</sup>, which  
108 corresponds to  $\sim 6.5\%$  of Titan’s total surface. The Soi crater region contains 22 distinct  
109 geomorphological units many of which were found in the Afekan (Malaska et al., 2016a) and  
110 South Belet regions (Schoenfeld et al., 2021).

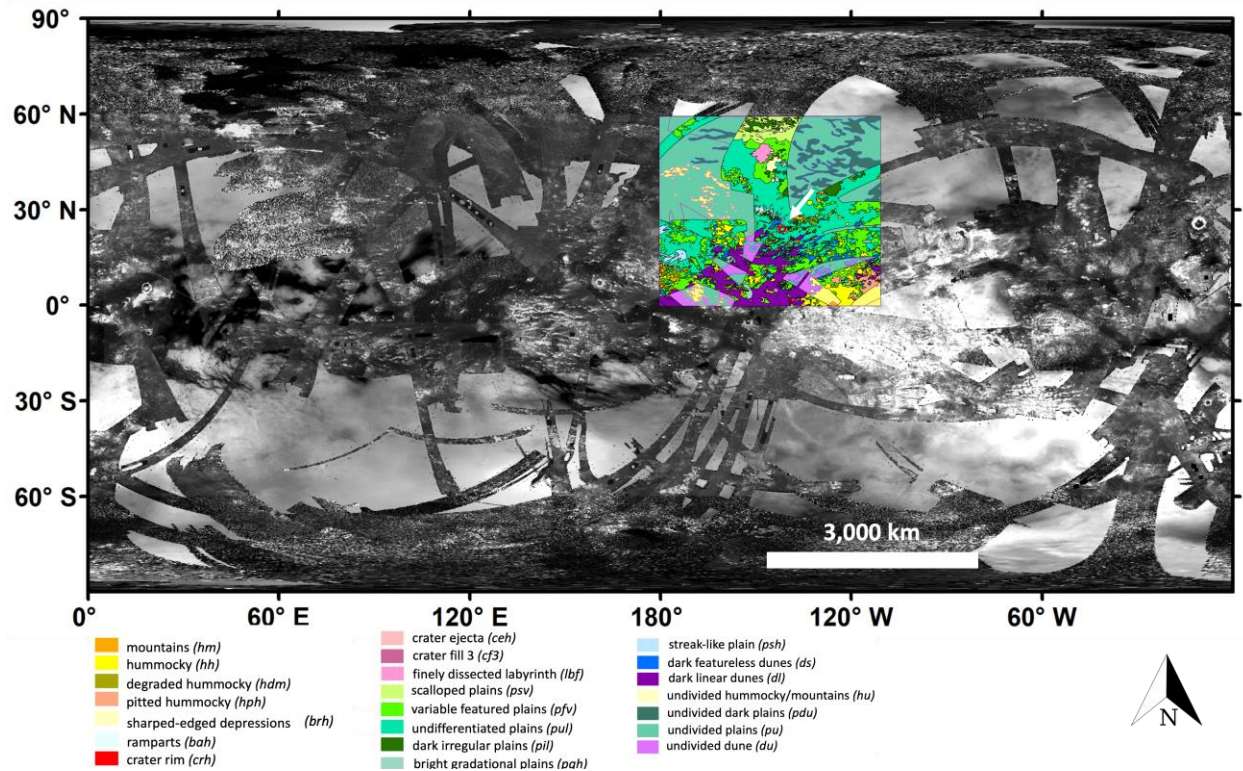
111 The geomorphological map presented in Schoenfeld et al. (2023) used SAR and non-SAR  
112 datasets including altimetry, Radiometry-Emissivity, ISS, and VIMS (Fig. 1). All the different  
113 Cassini data used to create the geomorphological map of the Soi crater region (SAR, HiSAR,  
114 SARTopo and Digital Terrain Model, emissivity, VIMS, and ISS data) can be seen in Figure 2 of  
115 Schoenfeld et al. (2023). The 22 geomorphological units identified include features of empty lakes,  
116 mountains, dunes, craters, labyrinth, and vast plains (Table 1). The Soi crater region is dominated  
117 by plains, matching the general trend around Titan’s globe (see Lopes et al., 2020), followed by  
118 dunes, mountainous terrains, and finally very few craters and empty sharp-edged depressions

119 (SEDs) (Table 1). As for most of Titan, impacts have been erased by more recent geological  
 120 processes, likely those that form dunes and plains.  
 121

122 **Table 1.** Terrain class, terrain units, terrain unit code found in the Soi crater region. Details,  
 123 locations, and descriptions of the units are in Table 1 of Schoenfeld et al. (2023). The letter codes  
 124 followed here are based on mapping efforts that have followed the general principles of previous  
 125 Titan mapping and other planetary mapping efforts (Greeley and Batson, 1990; Greeley et al.,  
 126 2000; Patterson et al., 2010; Williams et al., 2014; Lopes et al., 2016; 2020; Malaska et al., 2016;  
 127 2020; Schoenfeld et al., 2021; 2023).

Terrain class/ % of total area	Terrain unit name and code
<b>Plains (73%)</b>	Undifferentiated plains ( <i>pul</i> )
	Variable plains ( <i>pfv</i> )
	Scalloped plains ( <i>psv</i> )
	Dark irregular plains ( <i>pil</i> )
	Streak-like plains ( <i>psh</i> )
	Bright gradational plains ( <i>pgh</i> )
	Undivided plains ( <i>pu</i> )
	Undivided dark plains ( <i>pdu</i> )
<b>Dunes (14%)</b>	Featureless sand sheets ( <i>ds</i> )
	Linear dunes ( <i>dl</i> )
	Undivided dunes ( <i>du</i> )
<b>Mountains / Hummocky / Labyrinth (12%)</b>	Mountain ( <i>hm</i> )
	Hummocky ( <i>hh</i> )
	Degraded hummocky ( <i>hdm</i> )
	Pitted hummocky ( <i>hph</i> )
	Finely dissected labyrinth ( <i>lbf</i> )
<b>Craters (&lt;1%)</b>	Undivided mountain chains/hummocky areas ( <i>hu</i> )
	Crater rim ( <i>crh</i> )
	Crater ejecta ( <i>ceh</i> )
<b>Lakes (&lt;1%)</b>	Crater fill 3 ( <i>cf3</i> )
	Sharp-edged depression ( <i>bse</i> )
	Ramparts ( <i>brh</i> )

128



129

130 **Figure 1.** Geomorphological map of the Soi crater region (adapted from Schoenfeld et al., 2023)  
 131 in global context. Geomorphological map for all SAR and non-SAR data at zero transparency (map  
 132 layer fully opaque), same color scheme as the global geomorphological map of Titan in Lopes et  
 133 al. (2020). The arrow points to the Soi crater. The background map is a global mosaic of Titan  
 134 created from Imaging Science Subsystem (ISS) data (USGS Astrogeology Science Center).

135

### 136 3 Compositional mapping

137 Titan's surface composition remains, to this day, largely a mystery. Due to both  
 138 atmospheric effects and spectral degeneracies, we have so far been prevented from making  
 139 quantitative and accurate estimates of material concentrations within the numerous and varied  
 140 geologic units on Titan's surface. This is a complex situation that can only be improved in a step-  
 141 by-step approach in which every new constraint brings useful additional information, while  
 142 waiting for new observations from ground-based facilities or *in situ* data from space missions like  
 143 Dragonfly (e.g., Tobie et al., 2014; Lorenz et al., 2021; Barnes et al., 2021; Sulaiman et al., 2021;  
 144 Rodriguez et al., 2022). There are, however, select windows through Titan's atmosphere in the  
 145 near-infrared where the methane absorption is reduced (e.g., Barnes et al., 2005; Corlies et al.,  
 146 2021). Due to Titan's complex atmosphere and processes therein, we apply a radiative transfer  
 147 code to Cassini VIMS data in order to tackle as well as possible the issue of lingering methane  
 148 absorption and scattering of atmospheric components.

149 For the chemical compositional mapping, we used methods that have been successfully  
 150 used in the past on VIMS data (Bonnefoy et al., 2016; Lopes et al., 2016; Malaska et al., 2016a;  
 151 Brossier et al., 2018; Solomonidou et al., 2014; 2016; 2018; 2020a,b), to account for the  
 152 atmospheric contribution to the data and extract the actual surface information in the form of

153 albedo values and spectral responses. Further, similar to Solomonidou et al. (2018), where the first  
154 attempt of constraining the chemical composition of all major Titan geomorphological units was  
155 made, in addition to the compositional analysis of one specific unit, the impact craters  
156 (Solomonidou et al., 2020a), here we provide a compositional analysis of the entire Soi crater  
157 region in greater detail than in the previous efforts and for a significantly larger number of units  
158 and locations. Efforts to spectrally analyze Titan's vast areas and constrain their composition can  
159 be found in Nelson et al. (2006), McCord et al. (2006; 2008), Barnes et al. (2008), Brown et al.  
160 (2008), Clark et al. (2010), Soderblom et al. (2010), MacKenzie et al. (2014), Rodriguez et al.  
161 (2014), Brossier et al. (2018), Griffith et al. (2019), Coutelier et al. (2021) and others. All of these  
162 studies have analyzed VIMS data. Some of them have utilized radiative transfer codes (e.g., Coutelier et  
163 al., 2021) for their data analyses, while others have employed geophysical and remote sensing tools and  
164 methods such as Principal Component Analysis (PCA) (e.g., Griffith et al., 2019) and spectral ratios (e.g.,  
165 Barnes et al., 2008). These methods are often employed to highlight differences between features and to  
166 reduce the effect of varying light reflectance intensities. In Coutelier et al. (2021), the radiative transfer  
167 code is utilized to factor in atmosphere scattering and absorption, thereby eliminating atmospheric effects  
168 and discrepancies caused by observational geometries. The ultimate outcome is the retrieval of atmospheric  
169 albedos across all atmospheric windows. Their findings underscore a significant observation, which is  
170 compatible to findings of this present work: the relationship between water ice and VIMS 'dark blue' and  
171 'bright blue' areas is not as straightforward as previously believed (Barnes et al., 2007a, 2007b).

172 Our chemical composition map was created using the measurements of VIMS through our  
173 radiative transfer code (RT) and spectral deconvolution analysis. We recognize that the spectral  
174 analysis is only of the very thin optical layer (tens of microns) that covers the surface of Titan. To  
175 take into account the material below the optical covering, in our interpretations of the geological  
176 history of the area we also use the microwave emissivity measurements that probe the surface to  
177 greater depths (tens of centimeters). Microwave emissivity can be used to constrain the  
178 composition in depths that IR is unable to reach. Indeed, the radiometry provides a measure of the  
179 averaged emissivity of the near subsurface down to a depth that can be approximately defined as  
180 the electrical skin depth (Janseen et al., 2016). The sounding depth has been estimated based on  
181 the seasonal thermal signature in Janssen et al. (2009; 2016) and it is of the order of 40 cm - 1 m  
182 in the radar dark terrains, and to 200 m in liquid methane. This largely depends on the microwave  
183 transparency of the material, while the presence of high dielectric constant materials and/or volume  
184 scattering due to the presence of structures in the subsurface, are considered factors that decrease  
185 the emissivity values (Janssen et al., 2016).

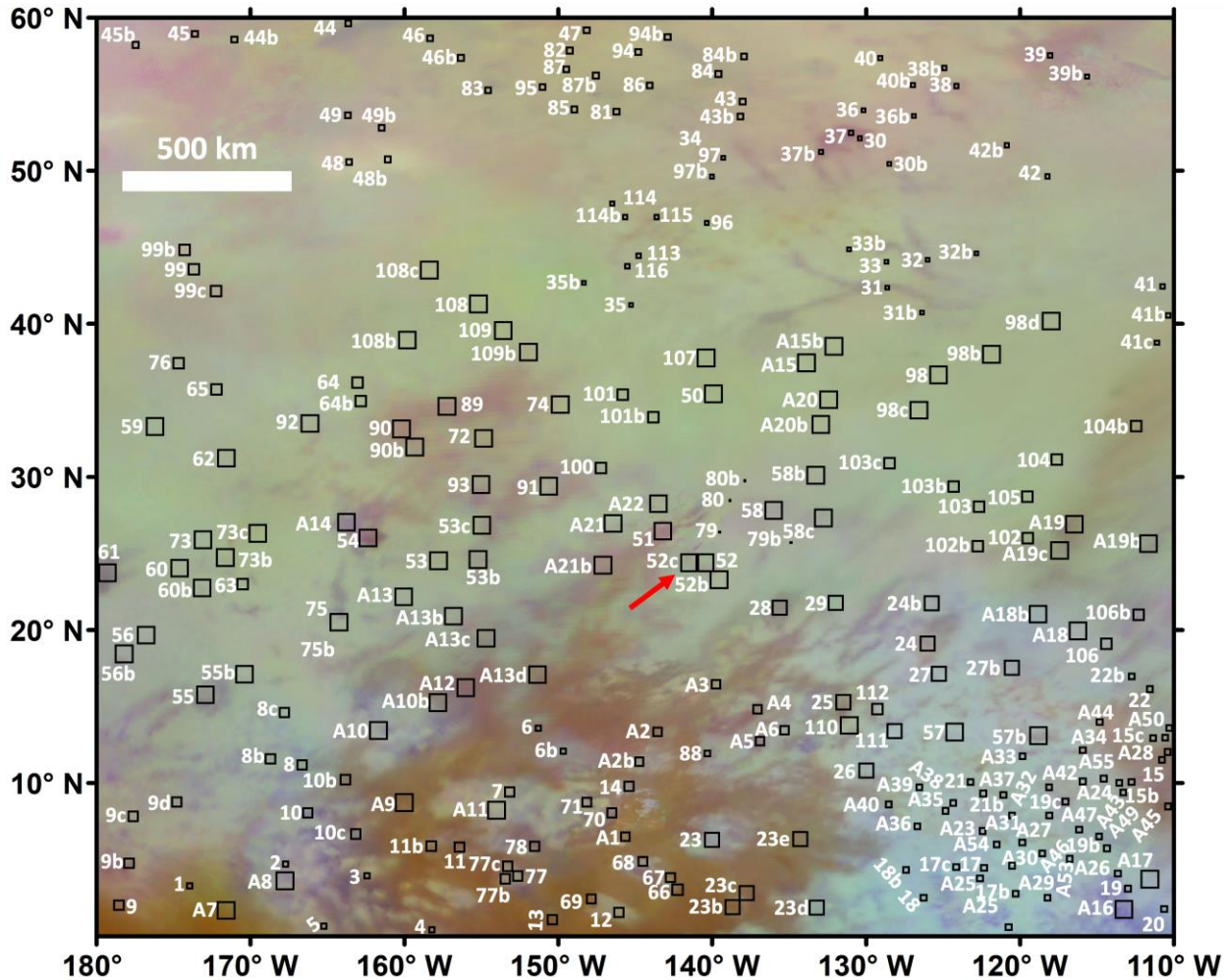
### 186 3.1 Radiative Transfer Technique and Mixing Model

187 The compositional results are extracted through a series of analyses of VIMS data. We have  
188 analyzed 261 different locations from within the Soi crater region using 14 VIMS datacubes from  
189 8 different Cassini flybys (Table 2; Figure 2). The selection of our 261 regions of interest (RoIs)  
190 was made after carefully examining the available VIMS datacubes compatible to our RT  
191 approximation and was based on the identification of pixels that thoroughly include different  
192 geomorphological units as described in Schoenfeld et al. (2013) in good resolution. We then used  
193 our RT code to extract surface albedos from the VIMS data (Hirtzig et al., 2013; Solomonidou et  
194 al., 2014;2016; 2018; 2020a;b).

195  
196 **Table 2.** Selected Cassini/VIMS datacube observations including flybys, dates of acquisition,  
197 product IDs, and cube properties (angles of incidence  $i$ , emergence  $e$ , and phase  $\alpha$ ; spatial  
198 resolution res).

Flyby	Date	Selected pixels with numbers as shown in Fig. 2 and product IDs	Datacube Properties Geometry-Spatial Resolution ( <i>i,e,a,res/pxl</i> )
Tb	12/2004	79-80: 1481629409	<i>i</i> : 52-53°, <i>e</i> : 15-17°, <i>a</i> : 36-37°, res: 03 km
T08	10/2005	A7-A31, A33, 98: 1509148649 50-58, 107-110: 1509149009 59-62, 72-75, 89-93: 1559085140	<i>i</i> : 30-57°, <i>e</i> : 09-46°, <i>a</i> : 23-24°, res: 46 km <i>i</i> : 34-60°, <i>e</i> : 26-42°, <i>a</i> : 22-23°, res: 45 km <i>i</i> : 49-60°, <i>e</i> : 26-42°, <i>a</i> : 25-26°, res: 39 km
T10	01/2006	1-6: 1516007480	<i>i</i> : 36-49°, <i>e</i> : 01-12°, <i>a</i> : 37-38°, res: 14 km
T12	03/2006	15-22: 1521407900 23-29, 111-112: 1521405451 A1-A6, A32, A34-A55: 1521402363	<i>i</i> : 29-37°, <i>e</i> : 34-55°, <i>a</i> : 65-66°, res: 15 km <i>i</i> : 45-57°, <i>e</i> : 19-38°, <i>a</i> : 64-65°, res: 38 km <i>i</i> : 54-59°, <i>e</i> : 11-41°, <i>a</i> : 63-64°, res: 23 km
T31	05/2007	63-66, 76, 99-106: 1559081653	<i>i</i> : 48-59°, <i>e</i> : 37-51°, <i>a</i> : 26-27°, res: 29 km
T77	06/2011	7-12, 14, 77-78b: 1687307753	<i>i</i> : 10-38°, <i>e</i> : 27-58°, <i>a</i> : 21-22°, res: 25 km
T97	01/2014	30-36, 96-97, 113-116: 1767303982 33b, 37-42: 1767303262 43-49, 81-88, 94-95: 1767301842	<i>i</i> : 33-49°, <i>e</i> : 10-28°, <i>a</i> : 51-54°, res: 10 km <i>i</i> : 43-60°, <i>e</i> : 08-30°, <i>a</i> : 52-53°, res: 12 km <i>i</i> : 32-44°, <i>e</i> : 11-22°, <i>a</i> : 55-56°, res: 16 km
T113	09/2015	13, 67-71: 1822165321	<i>i</i> : 37-59°, <i>e</i> : 02-09°, <i>a</i> : 57-58°, res: 14 km

199  
200



204 selected at each location based on their spatial resolution (see Table 2). The red arrow indicates  
205 the location of the Soi crater. North is at the top.

206  
207 Our RT code (Hirtzig et al., 2013) is a plane-parallel code based on a Spherical Harmonic  
208 Discrete Ordinate Method solver (SHDOMPP) (Evans, 2007) that incorporates: (a) the vertical  
209 profiles of temperature and pressure provided by the Huygens Atmospheric Structure Instrument  
210 (HASI) (Fulchignoni et al., 2005); (b) the methane vertical mixing ratio from the Gas  
211 Chromatograph Mass Spectrometer (GCMS) (Niemann et al., 2010); (c) a uniform CO mole  
212 fraction equal to  $4.5 \times 10^{-5}$  based on Cassini/CIRS measurements (de Kok et al., 2007); (d)  
213 atmospheric opacity sources from aerosols and gases: Rayleigh scattering from  $N_2$  and  $CH_4$  (Peck  
214 and Khanna, 1966; Weber, 2003); collision-induced absorption by nitrogen ( $N_2$ ) and hydrogen  
215 ( $H_2$ ) (McKellar et al. (1989); Lafferty et al. (1996); lines for methane (Campargue et al., 2015;  
216 TheoReTS - Rey et al., 2018) and its isotopologues (e.g.,  $^{12}CH_4$ ,  $^{13}CH_4$ ,  $^{12}CH_3D$ ) (HITRAN2020 -  
217 Rothman et al., 2013; Gordon et al., 2022); lines for CO and  $C_2H_2$  isotopologues (GEISA2009 -  
218 Jacquinet-Husson et al., 2011) with the use of correlated- $k$  absorption coefficients as described in  
219 Hirtzig et al. (2013). Considering all components (a-d), the code analyses the VIMS data and  
220 produces simulations of the surface albedo with various haze opacities.

221 The results are then calibrated with respect to the albedo measurements derived by the  
222 Descent Imager Spectral Radiometer (DISR) at the Huygens landing site (HLS), which we use as  
223 a reference area and a calibration tool. Given that the haze extinction profile reference is adjusted  
224 to the measurements from DISR, the haze contribution to the VIMS data at the landing site of  
225 Huygens is defined as 100%. By iteration for the best possible fit, the code derives the haze  
226 contributions with an absolute accuracy of  $\pm 5\%$  (Hirtzig et al., 2013). After estimating the haze  
227 population at all window wavelengths, the surface albedos are extracted at full spectral resolution  
228 and in weighted averages over each window's wavelength range (Tomasko et al., 2008; Hirtzig et  
229 al., 2013). In a weighted average, each data point value from within each of the 8 atmospheric  
230 windows is multiplied by an assigned weight, which is then summed and divided by the number  
231 of data points. For this reason, a weighted average can improve the data's accuracy. In this current  
232 analysis, we calculated single points of weighted averages of the surface albedo within the  
233 windows, with larger weights for channels with higher transmittance around the center. The  
234 spectral resolution (Full Width at Half Maximum, FWHM) is about 13 nm below  $2.0 \mu m$ , increases  
235 up to 22 nm at  $4.2 \mu m$ , and decreases to 18 nm at  $4.8 \mu m$  (Brown et al., 2004). An example of  
236 weighted averages of the surface albedos in the atmospheric windows compared to the full  
237 resolution surface albedo spectrum in the  $0.89\text{--}5.2 \mu m$  of the Visual and Infrared Mapping  
238 Spectrometer range can be found in Figure 5 of Solomonidou et al. (2018).

239 In our RT code and the extraction of surface albedos, we consider several uncertainties  
240 calculated and summed at the  $3\sigma$  level including random errors due to noise in the data and due to  
241 propagation of haze retrieval errors, as well as systematic errors due to model, resulting from  
242 uncertainties due to the  $CH_4$  far-wings opacity, the  $CH_4$  linelist, the  $CH_4$  vertical concentration  
243 profile, the aerosol phase function, the aerosol vertical distribution, and the aerosol forced single  
244 scattering albedo. All the details on the error estimation can be found in Section 3.3. in Hirtzig et  
245 al. (2013). In this current analysis we also take into account errors in the existing spectral line  
246 profiles, the haze extinction fit, the data intrinsic noise, which unlike random noise, is not random  
247 but arises from specific characteristics or imperfections in the sensor (McCord et al., 2004) and  
248 the phase function uncertainty. The surface albedos are then inverted with relative errors of 35%,  
249 35%, 26%, 21%, 26%, 50%, 50%, and 43% for the 0.94, 1.08, 1.28, 1.58, 2.03, 2.69, 2.79,  $5.00$   
250  $\mu m$  windows, respectively. At the longer wavelengths of  $2.69\text{--}5 \mu m$ , the uncertainties are larger



251 due to the lower signal to noise ratio (S/N). In any case, the error bars on the best fit of surface  
252 albedos take into account not only S/N limitations, but also errors due to uncertainties on the haze  
253 model (typical error on the extinction is 5%). Since the RT code adopts a plane-parallel and a  
254 Lambertian approximation and for the accuracy of the results, only VIMS data with geometry  
255 observations of both incidence and emergence angles  $<60^\circ$  are selected, with only 15% of the data  
256 selected having incidence or emergence angles  $>50^\circ$  (Table 2). We followed the approach used  
257 previously and in the recent study by Es-Sayeh et. al. (2023) where the authors use the RT code  
258 with the plane-parallel approximation used in this current analysis as well, and recommend the use  
259 of VIMS datacubes with incidence angles up to  $50^\circ$  incidence angle. The phase angle of all  
260 selected datacubes are higher than  $10\text{-}15^\circ$  and up to  $70^\circ$  and hence the surface behaves almost as  
261 Lambertian (Karkoschka et al., 2012). The effects of the phase angle on the I/F value are included  
262 in the error bars on our results (Karkoschka et al., 2012; Solomonidou et al., 2014). The spatial  
263 resolution of our selected datacubes ranges from 3 to 46 km/pixel (Table 2).

264 Finally, we use a linear mixing model, as in previous work (Solomonidou et al., 2018;  
265 2020a), to place semi-quantitative constraints on the relative composition of Titan’s surface. The  
266 model includes a selected spectral library of molecules, used as proxies for Titan candidate  
267 materials convoluted to VIMS spectral resolution, in order to examine the compositional properties  
268 of the various regions within the Soi crater region. While some of the specific molecules and  
269 complex carbonaceous materials included in our mixing model library are not expected to be found  
270 on Titan, we have used them to represent complex organic materials. Many of these materials are  
271 biogenic in origin, and through terrestrial diagenetic processes have become chemically  
272 aromatized and converted into complex refractory materials. The purpose of this exercise is not to  
273 imply exact chemical composition, but to constrain the relative types of molecular classes that  
274 could be present.

275 The Titan candidate materials include ices of ammonia ( $\text{NH}_3$ ), carbon dioxide ( $\text{CO}_2$ ), water  
276 ( $\text{H}_2\text{O}$ ), cyanoacetylene ( $\text{HC}_3\text{N}$ ), methane ( $\text{CH}_4$ ), tholins, kerite, asphaltite, three different types of  
277 anthraxolites, and amorphous carbon (Quirico and Schmitt 1997; Grundy and Schmitt 1998;  
278 Grundy et al., 2002; Bernard et al., 2006; Brasse et al., 2015; GhoSST @ SSHADE database).

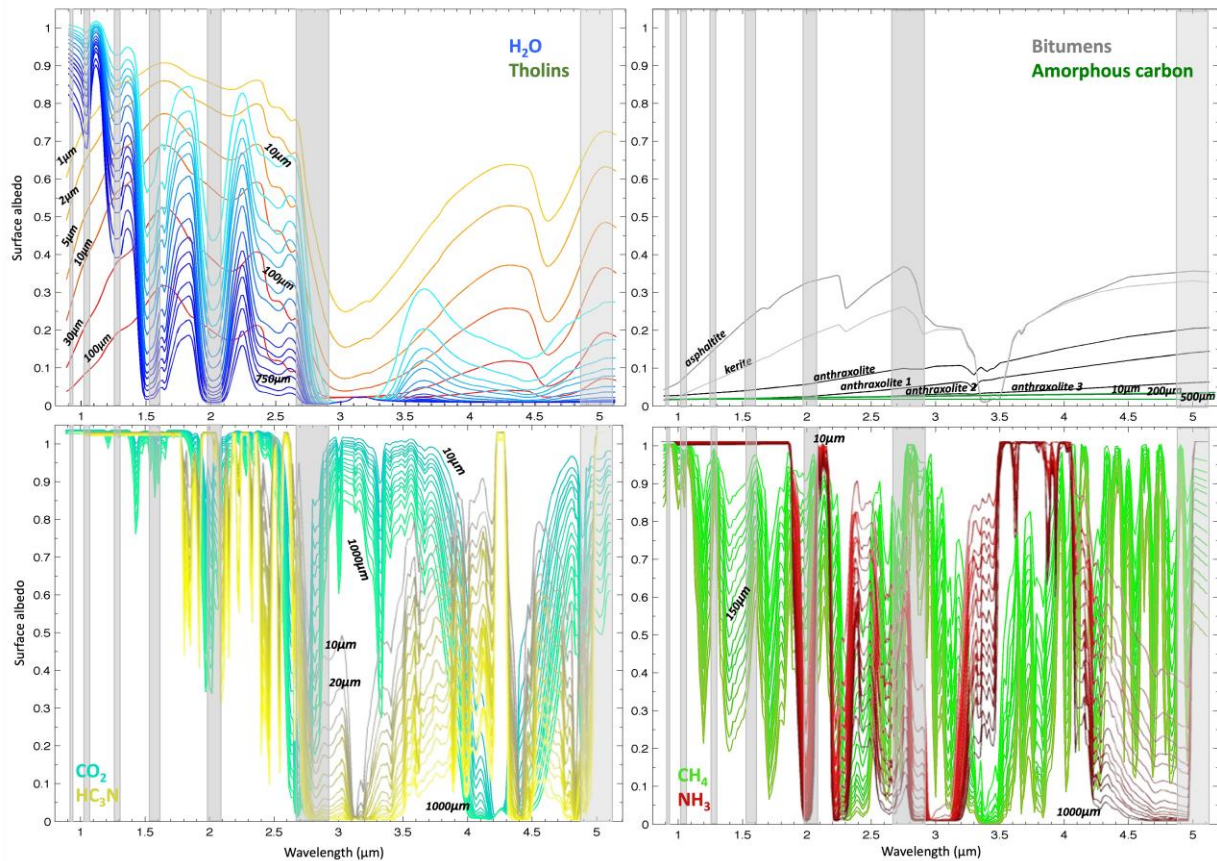
279 Tholins are laboratory-produced materials which may differ from the complex aerosols  
280 produced in Titan’s atmosphere and later processed at the surface by fluvial/pluvial/aeolian  
281 activity. However, their spectral properties have been used in Titan’s spectral analyses to simulate  
282 the atmospheric haze content.

283 We use ‘methane’ as a representative for any aliphatic hydrocarbon solid including  
284 alkanes, alkynes, and alkenes (e.g., Lora and Ádámkóvics, 2017; Malaska et al., 2017; Faulk et  
285 al., 2017; 2020). These other solid aliphatic materials may be part of the compositional mix,  
286 however, these larger aliphatic materials will not be liquid since at Titan temperatures only  
287 methane, ethane, propane, and 1-butene are liquid. As a proxy for solid materials, methane does  
288 not have measurable significant position shifts (i.e., any shifts are much smaller than VIMS  
289 resolution). In addition, the optical constants of methane remain virtually unchanged between  
290 liquid and solid at 93 K (Grundy et al., 2002). Thus, we use methane as a general proxy for  
291 materials (simple organics) although the spectral and optical constant properties of the actual  
292 materials could be much more complicated.

293 The data of the icy components have been calculated with the ‘SPECTRIMAG’ radiative  
294 transfer code for granular surfaces (Douté and Schmitt, 1998), in sets of 15 different pathlengths  
295 spanning 2 orders of magnitude. All components in the constituent library are in the VIMS  
296 spectrum and hence simulations with the extracted RT albedos are possible. The mixing model fits  
297 the RT extracted albedos with the most compatible mixture of the proxy constituents and linear  
298 mixtures thereof, inferring at least 4 constituents (Solomonidou et al., 2018; 2020a). The model  
299 provides compositional constraints using the limited number of available atmospheric windows

300 and that entails that there is no unique solution for the mixtures. A perfect fit cannot be achieved  
301 between the simulations and the observations because all radiative transfer codes are incapable of  
302 totally reproducing the complexity of Titan's system (atmosphere, surface, and interactions among  
303 these convoluted elements) and no simple mixture of components can reproduce what exists on  
304 the surface of Titan. Our method tests to what extent the available observations (absolute values  
305 and spectral shape) can be match with these basic constituents. The code output includes estimated  
306 errors of the derived abundances of the different components of the mixture.

307 Bitumens are used as proxies to lower the total surface albedo (Moroz et al., 1998; Lellouch et  
308 al., 2004; Court et al., 2006; Combe et al., 2007; Hirtzig et al., 2012) as it is expected to be low for  
309 Titan. Bitumen on Earth is a very complex intractable mixture containing many hydrocarbon and  
310 functionalized hydrocarbon components. It derives from coal and petroleum residues which in turn  
311 derived from diagenetically processed humic acids, steroids, and wax lignins from buried (usually  
312 vegetative) biologically produced organic matter. It is not likely that bitumen as produced on Earth  
313 would be exactly present on Titan. However, in the absence of another good analogue for dark  
314 materials we have applied this component as a proxy in our simulations. In particular, bitumen  
315 contains a large amount of naphthene aromatics (naphthalene), consisting of partially  
316 hydrogenated polycyclic aromatic compounds. We use these as a proxy for complex mixtures of  
317 Titan aromatic molecules that fused and linked such as (for fused) phenylacetylene, naphthalene,  
318 and phenanthrene (Abplanalp et al., 2019) and linked aromatics such as biphenyl, terphenyl and  
319 higher homologs. All solid small-molecule organics included in the spectral library are in 15 grain  
320 sizes (10, 20, 30, 40, 50, 75, 100, 150, 200, 250, 300, 400, 500, 750, and 1,000  $\mu\text{m}$ ), the laboratory  
321 tholins in 6 grain sizes (1, 2, 5, 10, 30, and 100  $\mu\text{m}$ ), and the amorphous carbon in 3 grain sizes  
322 (10, 200, and 500  $\mu\text{m}$ ) (Quirico and Schmitt, 1997; Grundy and Schmitt 1998; Grundy et al., 2002;  
323 Bernard et al., 2006; GhoSST @ SSHADE solid spectroscopic database). Hence, in total we  
324 examined 90 different spectral possibilities. The spectra data used in this study in the VIMS range  
325 can be seen in Figure 3.



327

328 **Figure 3.** Spectra data of candidate components used in this work adapted from Solomonidou et  
 329 al. (2020a). H<sub>2</sub>O in shades of blue; laboratory tholins in shades of orange; bitumens in gray, and  
 330 amorphous carbon in dark green; CO<sub>2</sub> in shades of turquoise, and HC<sub>3</sub>N in shades of yellow; CH<sub>4</sub>  
 331 in shades of light green, and NH<sub>3</sub> in shades of red. These spectra are plotted in the spectral range  
 332 of VIMS at different grain sizes (Bernard et al. 2006; Brassé et al. 2015; GhoSST database,  
 333 <http://ghosst.osug.fr>). The light gray columns correspond to Titan's atmospheric windows.  
 334

### 335 3.2 Haze Estimations and Surface Albedos

336 The VIMS datacubes shown in Table 2 were acquired at different observational properties  
 337 and at different times during the Cassini mission (Tb – T113: 2004-2015). The analyzed VIMS  
 338 pixels from the 261 different locations are expected to include different atmospheric effects, which  
 339 is something that has been found to occur even at adjacent pixels from within the same VIMS  
 340 datacube (Solomonidou et al., 2016; 2018). Indeed, the analyses of the VIMS data from the various  
 341 locations within the SoI crater region showed that the haze contributions to the VIMS data ranges  
 342 from 70-130% ( $\pm 5\%$ ) with respect to the Huygens Landing Site DISR measurements used a  
 343 calibration point (Karkoschka & Tomasko, 2010). In particular, the haze contribution to the data  
 344 seems to present a relative dependance with latitude. Datacubes from flybys Tb, T08, T10, T12,  
 345 and T77 that cover mostly low to mid latitudes when treated with RT the haze estimation ranges  
 346 between 70-110%, while from T31 and T97 that cover mostly higher latitudes range from 100-  
 347 130%.

348 The examples of extracted surface albedos in the form of weighted averages are shown in  
349 Figure 4, including one example for each geomorphological unit and their various types. There are  
350 four groups based on their geomorphological characterization: (a) dunes; (b) highlands such as  
351 mountainous/hummocky and labyrinth terrains; (c) crater units and SEDs; and (d) plains. In Figure  
352 4 the extracted albedo from HLS is also present for comparative purposes.

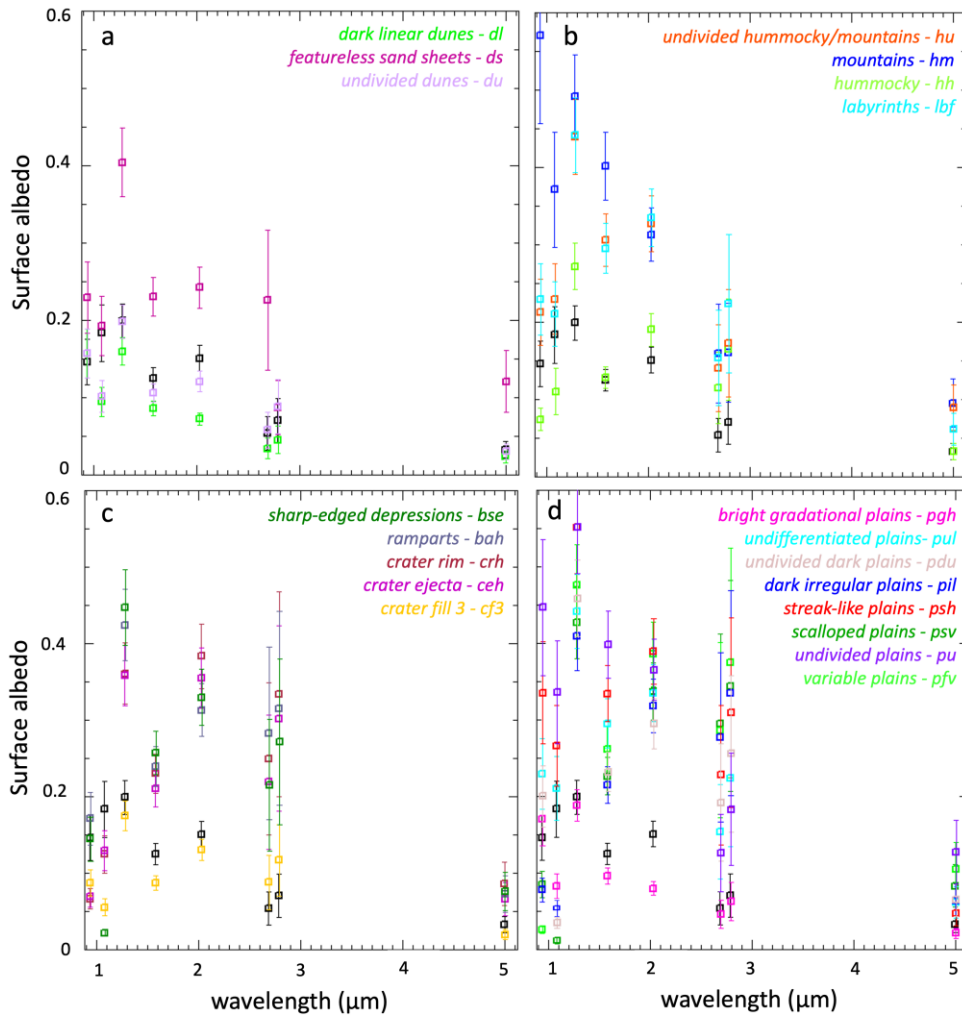
353 The overall albedo values of the dunes (Fig. 4a) at all wavelengths are among the lowest  
354 compared to the rest of the units, as demonstrated in previous studies (e.g., Soderblom et al., 2007;  
355 Barnes et al., 2008; Rodriguez et al., 2014; Bonnefoy et al., 2016; Solomonidou et al., 2016; 2018;  
356 Brossier et al., 2018). The featureless sand sheets (*ds*) present much brighter albedos than the other  
357 types of dunes, which we find correlated with their locations, as they appear mostly over 15°N and  
358 are completely absent from the equator. The dark linear dunes (*dl*) and the undivided dunes (*du*)  
359 have similar spectral behavior and albedo values within error bars at all wavelengths, except for  
360 the 2 μm window where the dark linear dunes have particularly low albedo, suggesting the  
361 presence of a constituent very absorbent at this wavelength. The lower albedo at all wavelengths  
362 for units closer to the equator is attributed to the transport and incorporation of dark material from  
363 the dunes due to aeolian transport processes (Malaska et al., 2016b; Lopes et al., 2016;  
364 Solomonidou et al., 2018; 2020a).

365 The highland terrains (Fig. 4b) present differences in their surface albedos, with the  
366 hummocky terrains (*hh*) having low albedo values, agreeing with the results in Solomonidou et al.  
367 (2018), and the mountainous terrains (*hm*) presenting significantly high albedo values, especially  
368 at the short wavelengths (0.94-2 μm). Interestingly, the undivided hummocky/mountainous  
369 terrains (*hu*) have albedo values in between the values of hummocky and mountainous terrains as  
370 shown in Fig. (4b). The labyrinth terrains (*lbf*) present relatively high surface albedos, with spectral  
371 similarities with the undifferentiated plains (*pul*) (Fig. 4d)

372 The albedos extracted from crater subunits (Fig. 4c) show that the crater fill 3 (*cf3*) is filled  
373 with the same material that is present in the dunes. The crater rim and crater ejecta show very  
374 similar spectral behavior and albedo values within error bars, something that was also shown for  
375 the Soi crater subunits in Solomonidou et al. (2020a). The albedos of the sharp-edged depressions  
376 (*bse*) and of their ramparts (*brh*) are intermediately bright with high values at the double window  
377 (2.69-2.79 μm) and the 5 μm window, similarly to the albedos extracted from VIMS data of three  
378 empty lake floors at 69°N-134°W in Solomonidou et al. (2020b). This study found that the material  
379 of the high-latitude empty lake floors is the same as the material of the raised ramparts that appear  
380 surrounding less than 10 SEDs of the north pole, suggesting that the ramparts are spectrally distinct  
381 from the surrounding plains.

382 Finally, the plains (Fig. 4d) present a great variety of different albedo values, with the new  
383 unit of gradational plains (*pgh*) having the lowest albedo of the plains units, marginally close to  
384 that of the dark linear dunes, following the dark linear dunes' drop in albedo from 1.59 to the 2  
385 μm window; a decrease that is not frequently observed in Titan's albedos. The dark irregular (*pil*),  
386 the undifferentiated (*pul*), the undivided dark (*pdu*), and the variable (*pfv*) plains present  
387 intermediate albedo values at the short wavelengths. The *pfv* is particularly bright at long  
388 wavelengths and the *pil* are very bright at the 2.69-2.79 μm double window. This brightness of  
389 Soi's *pfv* units at the 2.69-5 μm range was not observed in other locations of variable plains  
390 analyzed in Solomonidou et al. (2018) and seems compatible with the high latitude location of the  
391 Soi region variables that reach 50° N. The scalloped plains (*psv*) present intermediate to high  
392 albedo values at most wavelengths. The streak-like (*psh*) plains are very bright at all wavelengths,  
393 agreeing with the results in Solomonidou et al. (2018) and Lopes et al. (2016), while the newly

394 introduced undivided plains present high albedos at shorter wavelengths (0.94 – 2  $\mu\text{m}$ ), as well as  
 395 at 5  $\mu\text{m}$ .  
 396

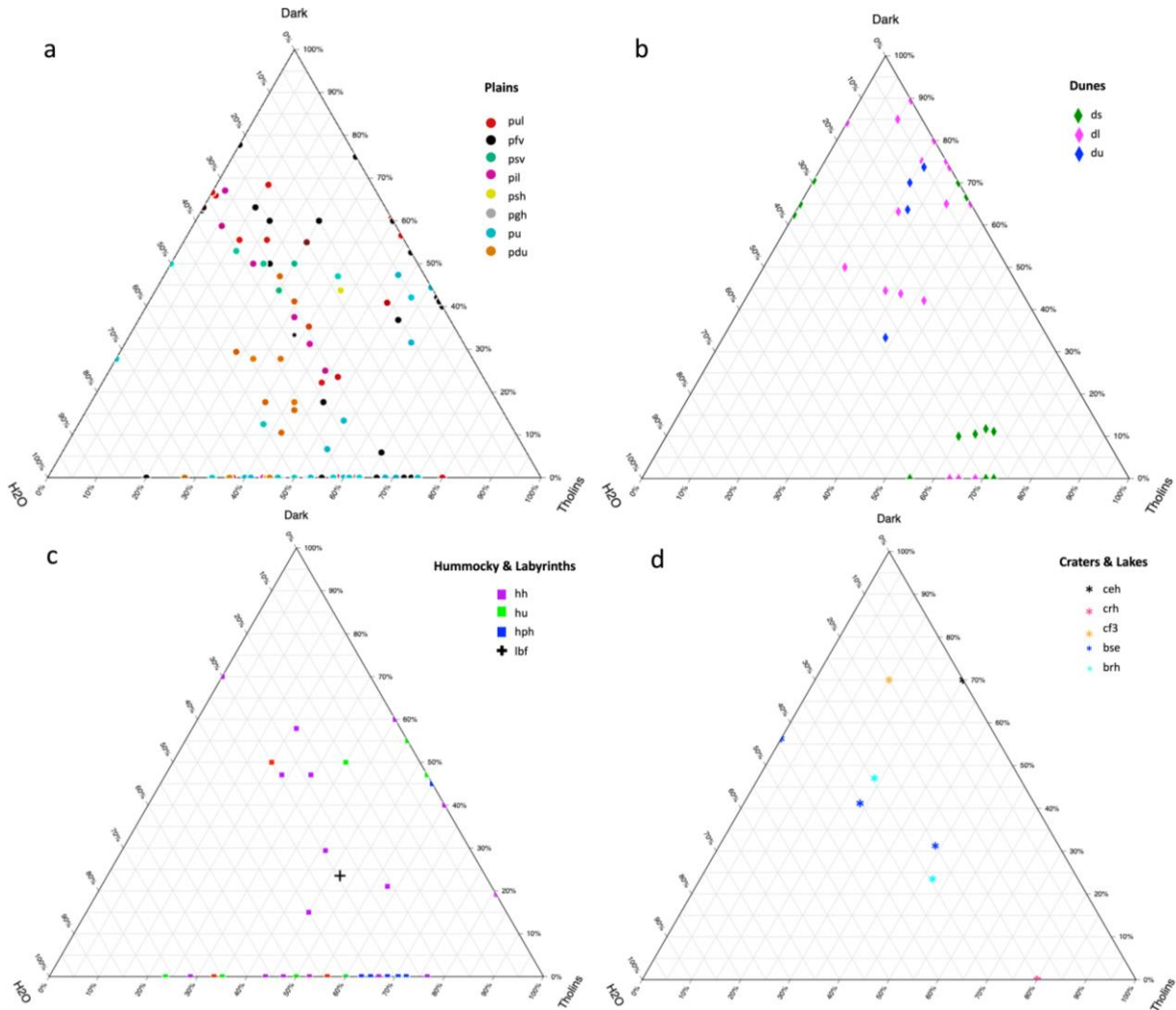


397  
 398 **Figure 4.** Examples of surface albedo weighted averages in the atmospheric windows as extracted  
 399 from VIMS data with RT for four different groups of units: (a) dunes; (b) hummocky/mountainous  
 400 and labyrinth; (c) impact crater units and sharp-edged depressions; and (d) plains. The Huygens  
 401 Landing Site (HLS) albedos (in black) are used as reference.

402 **3.3 Surface Mixtures**

403 The extracted albedos presented in the previous section are used in the mixing model to  
 404 provide linear mixture simulations that would fit the albedo data in the most optimal way, given  
 405 the available albedo points and the candidate Titan materials in the spectral database, and from the  
 406 perspective of what can be done in such a complex situation with limited available *in situ*  
 407 observations. Even if the fits between the mixture simulations and the albedo data are not perfect,  
 408 they provide insights into the surface composition of Titan’s top surface layer, which is still  
 409 unknown even after 13 years of Cassini exploration (e.g., Nixon et al., 2018; MacKenzie et al.,  
 410 2021). Table 3 includes the results from all 261 locations and Figure 5 presents ternary diagrams  
 411 for the composition of plains (a), dunes (b), hummocky terrains and labyrinths (c), and craters and

412 lakes (d). Examples of the mixture simulation results from representative units within the Soi crater  
 413 region can be found in Figure 6. The  $\chi^2$  values from the analyzed areas range from 0.24 to 3.48,  
 414 suggesting high correlation between the mixture simulations and the albedo data. From first read  
 415 of Figure 5 it seems that the majority of plains (5a) and hummocky and labyrinth terrains (5c) are  
 416 lacking the contribution of the dark organic material in their mixtures, something that as expected  
 417 the dunes (5b) have in abundance. The empty sharp-edged depressions, their surrounding ramparts,  
 418 and craters on the other hand seem to have a combination of all three constituents in their mixtures.  
 419



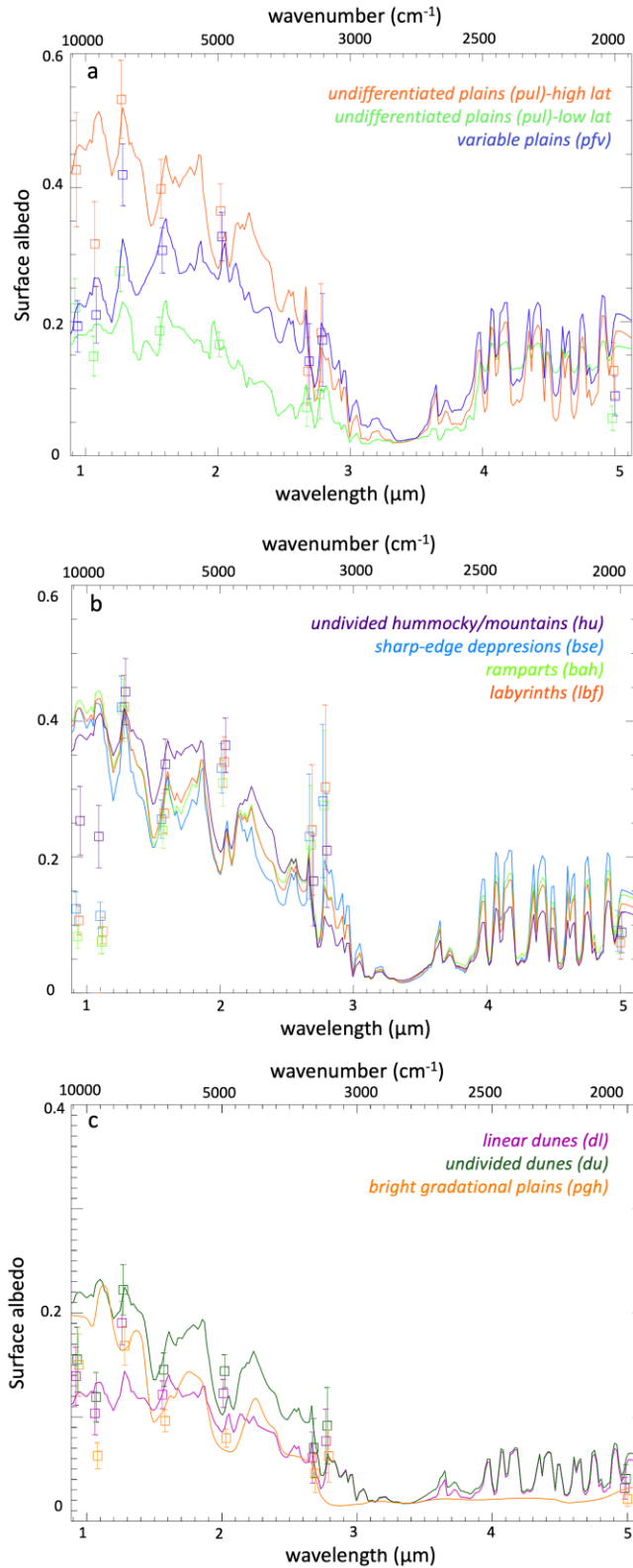
420  
 421 **Figure 5.** Ternary diagrams representing a composition from the three major constituents: H<sub>2</sub>O,  
 422 tholin-like constituent, and unknown dark constituent. (a) various types of plains; (b) various types  
 423 of dunes; (c) various types of hummocky terrains and labyrinths; (d) different parts of craters and  
 424 lake features. Detailed compositional constraints for each unit and their various locations can be  
 425 found in Table 3.

426  
 427 In our attempts to understand the chemical composition of Titan's surface as well as  
 428 possible, the code provides simulations of mixtures including at least four major constituents,  
 429 based on which we built our compositional map for the Soi crater region (see following section).  
 430 It was particularly difficult to reproduce in some cases the 0.94 and 1.08  $\mu\text{m}$  albedo values,

431 something that was previously found in Solomonidou et al. (2020a), when studying the  
432 composition of Titan's major impact craters. Furthermore, in Solomonidou et al. (2018) in a similar  
433 attempt to characterize the composition of the surface, fewer compounds were added from the  
434 library, which led to a worse fit especially for 0.94, 2.03, and 2.79 $\mu\text{m}$ . In this present study we  
435 have added more components in our simulation, increasing the number of component spectra  
436 available for potential matches in our library from 75 to 90, when taking into account the grain  
437 sizes. For the latter, the best fits are obtained using spectra from specific grain sizes for the different  
438 components since the albedo can be very dependent on the grain size, as shown in Figure 3. For  
439 the areas where their mixture includes tholins, the best fits are obtained using 30 $\mu\text{m}$  and 100 $\mu\text{m}$   
440 tholins. For CH<sub>4</sub> ice, the optimal grain size is 1000 $\mu\text{m}$ , while for H<sub>2</sub>O ice, it ranges from 10 $\mu\text{m}$  to  
441 50 $\mu\text{m}$ . Finally, among the various bitumens, the ones that provide the best fit with the extracted  
442 albedos are amorphous carbon at 200 $\mu\text{m}$  and 500 $\mu\text{m}$ , along with asphaltite.

443 In all 261 cases, we obtained matches within error bars in at least four out of the eight  
444 wavelengths. Such challenges in spectroscopic analyses for Titan have been faced by previous  
445 studies for both ground-based and Cassini-Huygens observations and measurements (VIMS,  
446 DISR) (Coustenis et al., 1995; Smith et al., 2005; Tomasko et al., 2005; Brown et al., 2006; Clark  
447 et al., 2010; Soderblom et al., 2007). Here, the matches that are more difficult to achieve are at the  
448 very short wavelengths, and for some cases the double window (2.69-2.79  $\mu\text{m}$ ), and the 5  $\mu\text{m}$   
449 window. The mismatch, especially at the shorter wavelengths, is indicative of the limitations set  
450 by the VIMS data, the modeling, and the variability of the material library compared to the  
451 expected complexity of Titan's surface. In contrast to previous surface composition simulation  
452 studies (Solomonidou et al., 2018; 2020a), here we are better able to match the 2  $\mu\text{m}$  and the 2.79  
453  $\mu\text{m}$  albedo data with mixtures of components. Furthermore, we have a match at 1.59  $\mu\text{m}$  in almost  
454 all 261 regions. In addition, some units present very low albedo values at short wavelengths and  
455 there is conspicuous absence of fit at 1.08 $\mu\text{m}$  compared to other units. Particularly intriguing are  
456 the SEDs, ramparts, and labyrinths, which exhibit markedly low albedos at short wavelengths and  
457 comparatively higher values at 2.03 and double-window wavelengths (Fig. 6b). This characteristic  
458 poses challenges for fitting all atmospheric windows, as the code uses materials within the current  
459 databases exhibiting absorption at short wavelengths while strongly reflecting light within the  
460 2.03-2.79 $\mu\text{m}$  range. Further work on the Cassini data, along with the advanced development of  
461 tools for their processing and additional data from future missions (e.g., Dragonfly) and  
462 observations (e.g., JWST), will help us better understand the reasons behind these mismatches and  
463 provide solutions for improved fits between the albedos and the simulated surface mixtures.

464 In the next section we discuss in detail the compositional behavior of each unit. In the next  
465 section we discuss in detail the compositional behavior of each unit.



466  
 467 **Figure 6.** Examples of inferred spectra based on modelled constituent mixtures of different units  
 468 in the Soi crater region. (a) Examples of an undifferentiated plain from over 30°N (*pul* -high lat),  
 469 from close to the equator (*pul* -low lat), and a variable plain (*pfv*). (b) Examples of a sharp-edged



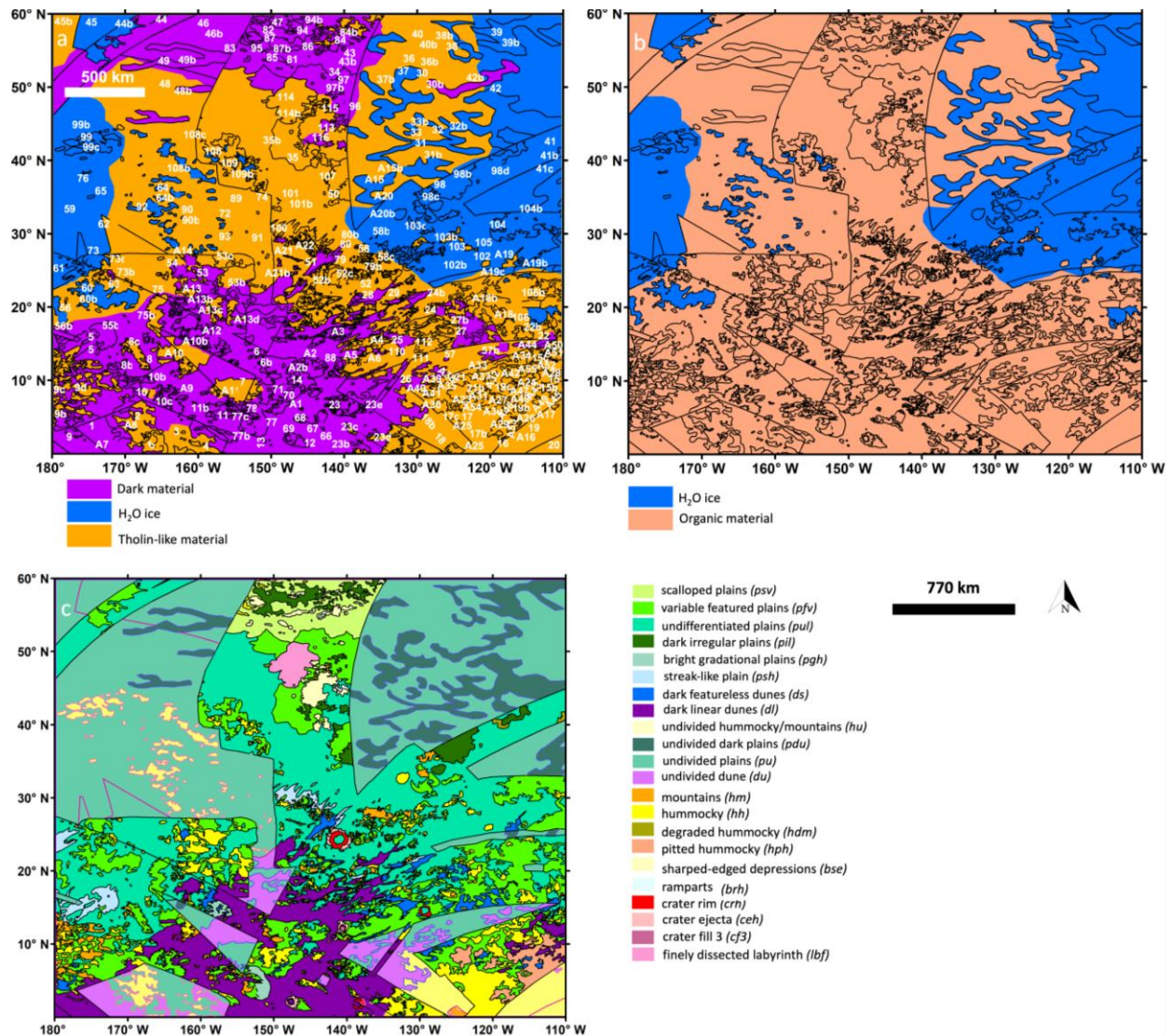
470 depression (*bse*), of its surrounding rampart (*brh*), a labyrinth terrain (*lbf*), and an undivided  
471 hummocky terrain (*hu*). (c) Examples of a linear dune (*dl*), an undivided dune (*du*), and a  
472 gradational plain (*pgl*). The point symbols correspond to extracted surface albedos from locations  
473 shown in Figure 2 and others, and the full lines to the compositional simulations, which are  
474 produced by the code using the best fit attained between the simulated spectra and the albedos.  
475 The  $3\sigma$  error bars are shown on the simulations and are inferred by the code during the extraction  
476 of the surface albedos (detailed description of the  $3\sigma$  error bars can be found in section 3.1).

#### 477 3.4. Spectral Class Compositional Map

478 The 261 locations (Figure 2) we analyzed with VIMS from the Soi crater region showed  
479 that it is a diverse region in terms of compositional variety for the visible surface (Figure 7; Table  
480 3). Figure 7a shows the extrapolated compositional results of the selected regions of interest as  
481 shown in Figure 2 with contact lines distinguishing the boundaries of the various  
482 geomorphological units of which we discuss their composition in detail in this section. In Figure  
483 7b, we classified the extrapolated composition from Fig. 7a into ice and organic material; the latter  
484 includes the dark material and tholins. Figure 7c shows the results from mapping of the Soi crater  
485 region as presented in Schoenfeld et al. (2023). Here, we do not attempt to provide exact molecular  
486 composition, given the limitations of the VIMS data described earlier, rather we treat each material  
487 as a representative for possible compositions of the upper layer of the surface. Our radiative  
488 transfer code takes into account a large number of uncertainties and translates them into error bars  
489 as described in section 3.1 and shown in Figures 4 and 6. Given those caveats, we provide  
490 constraints on the chemical composition of the surface through the classification of spectral types  
491 of materials, focusing on the major constituent of the mixture and up to the 4<sup>th</sup> constituent in  
492 abundance (Table 3). As a reminder, these maps represent compositional constraints of mixtures  
493 that possibly make up the very thin veil (few microns) that cover the surface. The deeper layers  
494 (few cms) of the surface and their composition are being discussed later in this section (subsection  
495 3.5).

496 We will examine each unit separately, however one result that is common for all analyzed  
497 locations in the Soi crater region is that we found no indication for the presence of significant  
498 amounts of carbon dioxide ( $\text{CO}_2$ ), cyanoacetylene ( $\text{HC}_3\text{N}$ ), or ammonia ( $\text{NH}_3$ ) ices in the mixtures,  
499 to within our aforementioned uncertainties.

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502  
 503 **Figure 7.** (a) Extrapolated composition map of the Soei crater region for the major constituents  
 504 from VIMS RT analysis and mixing model simulations with contact lines distinguishing the  
 505 boundaries of the various geomorphological units based on the boundaries drawn for the  
 506 geomorphological map in (c). The numbers represent the selections of regions of interest as  
 507 shown in Figure 2. The colored pixels are based on their compositional results for the major  
 508 constituent (blue for water-ice, magenta for dark organic material -a combination of bitumens and  
 509 amorphous carbon, orange for tholins). (b) Same as (a) with classification between ice (blue) and  
 510 organic (pink). (c) Geomorphological map for all SAR and non-SAR data (Schoenfeld et al., 2023)  
 511 at zero transparency (the map layer is fully opaque), same color scheme as the global  
 512 geomorphological map of Titan in Lopes et al. (2020).

513  
 514 All dune terrain units (*dl*, *du*, *ds*) have a primarily organic nature, but the different units  
 515 present differences in their secondary materials. The highland terrains (*hh*, *hm*, *hu*, *lbf*) lack a  
 516 characteristic major constituent among all their different units (Fig. 5c) and their nature depends  
 517 on their location. One common characteristic of all highland terrains is that they all appear to have  
 518 tholins in their mixtures (not as a major constituent) in significant amounts and that the presence

519 of CH<sub>4</sub>, as a tertiary or quaternary constituent, in their composition is stronger than in the dunes.  
520 The three crater units (*crh*, *ceh*, *cf3*) are primarily organic with the presence of water-ice only in  
521 the mixtures when the crater is located in regions dominated by plains (around the 30°N latitudinal  
522 zone), as shown in Solomonidou et al., (2020a). One such example is Soi crater. Furthermore, the  
523 composition of the empty sharp-edged depressions (*bse*) and their surrounding ramparts (*brh*) (Fig.  
524 5d) was found to be the same or very similar to those of the north polar empty lakes around 70°N  
525 discussed in Solomonidou et al. (2020b), which is a mixture of organics, water-ice, and simple  
526 organics. In Solomonidou et al. (2020b), it is noted that the emissivity of the northern raised  
527 ramparts points to a moderate-to-high contamination by organics. This emissivity is comparable  
528 to that of the northern empty basins. Combined with the VIMS results, this observation suggests  
529 that the ramparts and the empty lake floors, both located at the north pole, may share the same or  
530 similar composition. Here, as illustrated in Table 3 and discussed later in section 3.5, and similarly  
531 to the northern SEDs, the midlatitude empty SEDs are enriched in organic components.

532 The plains, in the same way as they present variable morphologies, present complex  
533 mixtures in their visible composition. The eight different units of plains are covered by different  
534 mixtures of materials. The recently introduced plain type (Schoenfeld et al., 2023), the gradational  
535 plains (*pgh*), is located close to the equator and below 20°N and is primarily organic in nature (dark  
536 material) and as shown in Fig. (4c) completely covered by dune materials. In contrast, the streak-  
537 like plains (*psh*) over 20°N do not include any dark material in their mixture and appear almost  
538 equally rich in water-ice and tholins. Similarly, the undivided dark plains (*pdu*), even though they  
539 were expected to be mostly abundant in the organic dark material due to their dark signature in  
540 VIMS, are instead relatively richer in water-ice, presenting some of the highest abundances in  
541 water-ice within the Soi crater region, along with the highland terrains. The undivided plains (*pu*)  
542 and the variable plains (*pfv*) are also covered by a mixture of organics and water-ice. The dark  
543 irregular plains (*pil*) and the scalloped plains (*psv*) are spectrally very similar, varying primarily in  
544 the amount of dark material present. Counterintuitively, the dark (in SAR) irregular plains, on  
545 average, have lower amounts of the dark material component than the scalloped plains. Previous  
546 analysis from a couple of scalloped plains (*psv*) from the region, which were analysed in  
547 Solomonidou et al. (2018) from older flybys (T25 and T94) than T97 (Table 2) and were found to  
548 be mainly abundant in water-ice, here are instead found to be abundant in the dark material (major)  
549 and water-ice (secondary). While our model uncertainties are significant, this may represent a  
550 change in the surface composition, which we hypothesize to be related to fluvial activity depositing  
551 a fresh overlying layer of dark material. Moreover, the dark irregular plains (*pil*) are mainly  
552 concentrated in latitudes higher than 30°N within the Soi crater region and were expected to be  
553 primarily rich in water-ice; however, even though water-ice is present in their mixtures, organic  
554 material seems to be the most abundant. Lastly, the undifferentiated plains (*pul*) seem to present a  
555 similar latitudinal dependence as shown in Solomonidou et al. (2018), with those in the 0-20°N  
556 zone being abundant in the dark material, while those in the higher latitudes being richer in water-  
557 ice (see Figure 7a;c). However, a large number of undifferentiated plains sample locations have  
558 tholins as the most abundant constituent, making these locations having the highest abundances in  
559 tholins. There is a significant amount of CH<sub>4</sub> in some cases reaching even 25% of the total mixture  
560 in some samples.

561 Detailed compositional constraints for each unit and their various locations can be found  
562 in Table 3. These are all suggestive compositional constraints and we acknowledge that they can  
563 be satisfied by other compositional solutions as well.

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### 3.5 Emissivity results

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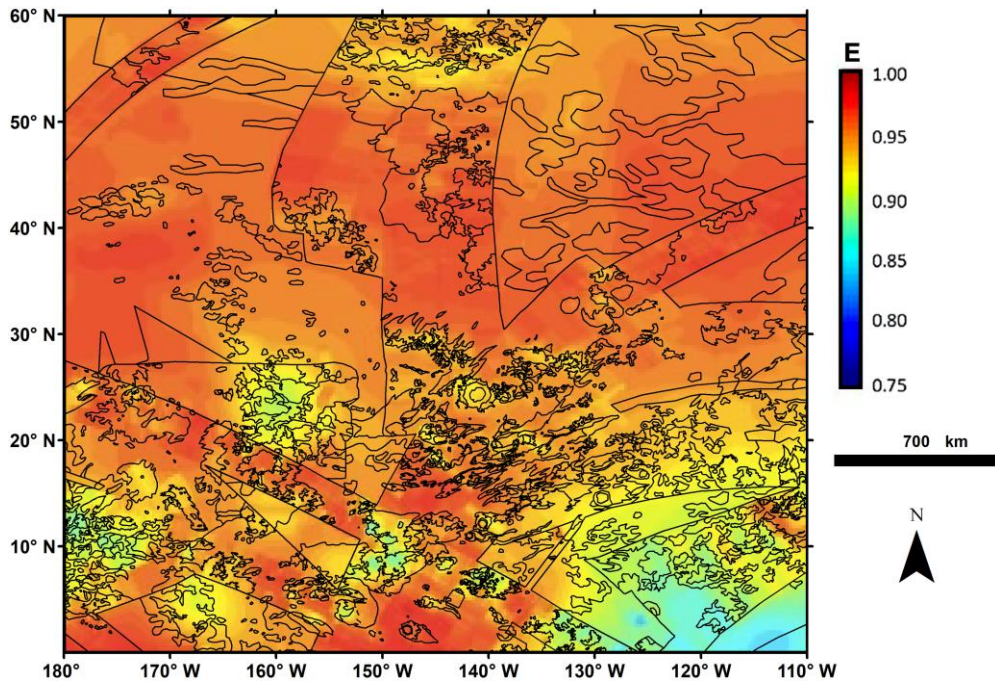
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As explained in Janssen et al. (2016) the presence of water-ice in the near subsurface is strongly indicated by the higher degree of volume scattering observed in radar-bright and low emissivity regions. Indeed, water-ice is highly transparent to microwaves, and therefore allows longer pathlengths which results in a higher probability for microwaves to encounter scatterers embedded in the subsurface. This in turn causes volume scattering, thus enhancing the radar cross-section and lowering the emissivity (Paillou et al., 2008; Janssen et al., 2016). A characteristic range of emissivity values for the different geomorphological units within the Soi crater region can be found in Table 1 in Schoenfeld et al. (2023) and the map of Figure 8. Though somewhat arbitrary, we interpret the units with values lower than 0.90 to be enriched in water-ice in their near subsurface (top decimeter of the regolith), and we interpret units with emissivity (E) values larger than 0.95 to be enriched in organic materials, and all values in between (E=0.90-0.95) to be consistent with a mixture of the two (Werynski et al., 2019; Malaska et al., 2020; Solomonidou et al., 2020a). The units that are more enriched in water-ice in their near subsurface (40 cm to 1 m) according to the emissivity values are the mountains, the hummocky terrains, and the undivided mountains/hummocky. The VIMS analysis agrees with the strong presence of water-ice in these units, which is always present in the mixtures of the top layer surface of these units; at few locations as major constituent (e.g., items 231-234 of Table 3) and except a very few regions of interest (e.g., items 192, 228 of Table 3) located near the equator which are completely coated with organic material (Table 3, items 191-249). However, a notable difference between the emissivity and VIMS/albedo results is the inconsistency in the major constituent of the mixtures at the southeast ‘corner’ of the Soi crater region of interest. Here, the emissivity data indicate a major water ice constituent (Fig. 8), while VIMS data suggest an organic one, specifically tholin-like material (Figs. 7a and 7b). The units that are more enriched in organic material according to emissivity are the dunes (*dl*, *ds*, *du*) with values ranging between 0.93 and 0.98. As shown in the previous section, the VIMS results of the top surface are in agreement with the organic nature of all types of dunes. Other units with strong organic nature according to emissivity include the undivided irregular plains (*pil*,  $E \geq 0.97$ ), the undifferentiated plains (*pul*,  $E \geq 0.97$ ), the undivided plains (*pu*,  $E \geq 0.96$ ), the undivided dark plains (*pdu*,  $E \geq 0.94$ ), the streak-like plains (*psh*,  $E \geq 0.95$ ), and the labyrinth terrains (*lbf*,  $E \geq 0.95$ ). The VIMS RT analysis of the top surface agrees with the organic appearance of *pil*, *pu*, and *pul* (depending on the latitude). However, the undivided dark plains and the streak-like plains appear more abundant in ice than organic material in the first few microns of their surface. It is important to note that the size and extent of the different features plays an important role in their emissivity measurements since small and thin patches of water-ice lying on an organic substrate may not be detected by radiometry. The rest of the units (*psv*, *pgh*, *du*, *cf3*, *ceh*, *ceh*, *brh*, and *bse*) have intermediate emissivity values suggesting a mixture of abundant icy and organic material with emissivity values ranging from 0.92 to 0.94. The VIMS analysis agrees with this icy and organic nature of the top surfaces of these units. Finally, the variable plains (*pfv*) present a large range of emissivity values (E=0.91-0.96) consistent with VIMS analysis suggesting a varying ice vs. organic nature for the unit depending on the location at all depths, from the thin  $\mu\text{m}$  veil covering the surface to 10’s of centimeters deep in the surface.



606  
 607 **Figure 8.** Emissivity map of the Soi crater region with contact lines distinguishing the boundaries  
 608 of the various geomorphological units. Emissivity data from Janssen et al. (2016).

609

## 610 **4 Geologic History of the Soi crater region**

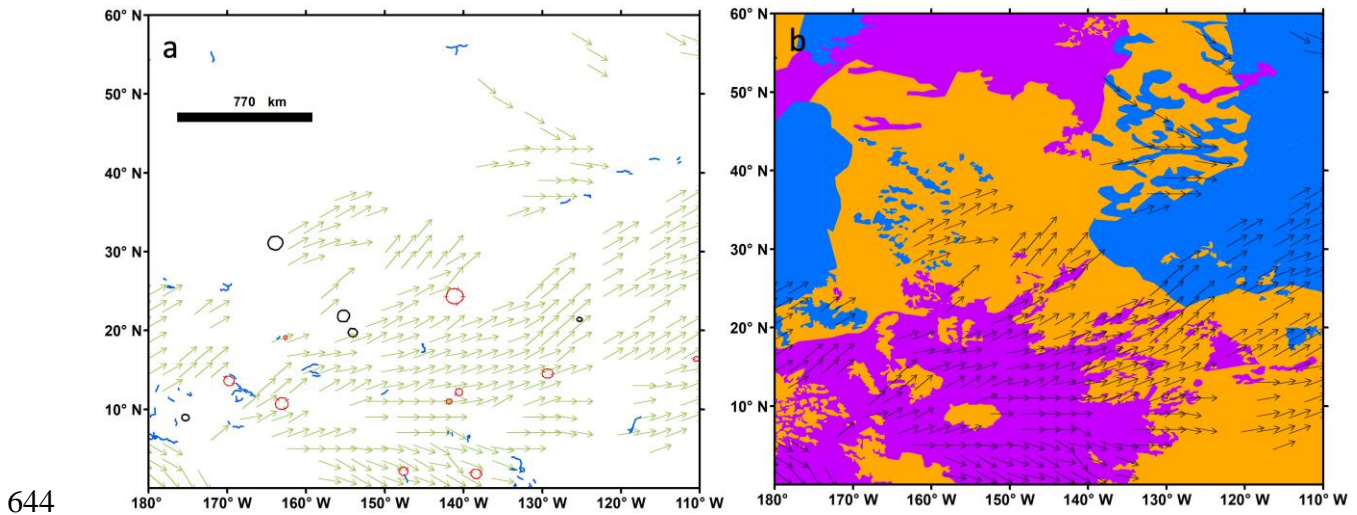
### 611 4.1 Surface Processes in Soi crater region

612 The Soi crater region is geomorphologically and compositionally variable, as shown in  
 613 Figure 7. In this section, we discuss the identified features from the various terrain types within  
 614 the region and we provide a geologic synthesis with respect to their chemical composition,  
 615 geomorphology, and potential geologic processes.

616 *Impact processes:* There are 10 impact craters identified within the Soi crater region (Wood  
 617 et al., 2010; Neish et al., 2015; Hedgpeeth et al., 2020; Schoenfeld et al., 2023). As also shown in  
 618 Figure 4c, where the differences in spectral responses between the ejecta and the floors are subtle,  
 619 the Soi crater region includes characteristic examples of how erosion affects the floors of the  
 620 craters by allowing dune material to intrude and deposit organic sand.

621 *Inferred Material Transport:* Wind and material transport models (Malaska et al., 2016b)  
 622 have helped distinguish different processes for the Soi crater region. Schoenfeld et al. (2023)  
 623 presented the sketch map of inferred material direction for the region, which we combined with  
 624 the map of chemical composition and present in Figure 9. The directions were based on alignments  
 625 and tapering morphologies of dunes, windstreaks and other terrains which enable the transport  
 626 direction to be inferred, for details see Malaska et al., (2016b). The map of chemical composition  
 627 correlates well with the flow path as shown in Figure 9b, with “extensions” of materials suggesting  
 628 that aeolian transport and subsequent deposition influences surface composition through delivery  
 629 of fine-grained saltating material (e.g., Schurmeier and Dombard, 2018). For example, in Figure  
 630 9b, extended “fingers” of dune materials (purple) are in the tholin-like plains zone (orange area).  
 631 While the inferred transport direction was determined from geomorphology (primarily by SAR),

632 it also appears to correlate to the compositional retrieval as well. This compositional analysis  
 633 further shows that the majority of the equatorial and low latitudes (0-20°N) are dominated by the  
 634 dark organic material that transition into an area more dominated by tholin-like materials in the  
 635 midlatitude. Similarly, mid to high-latitude zone with dark organic spectral components at 50-  
 636 60°N transitions to tholins in the midlatitudes (below 50°N) in a similar fashion. The areas rich in  
 637 water-ice appear over 20°N and they are suspected to be unrelated to material transport and  
 638 deposition and may be more connected to erosional processes. One possible mechanism that could  
 639 explain these observations would be a surface deposit of equatorially-derived mixed materials,  
 640 including water-ice and dark materials, which following deposition in the midlatitude plains either  
 641 have the coating removed (possibly through dissolution/leaching) to reveal a water ice-  
 642 enriched/tholin lag, or deposition with later coating from bright tholins from atmospheric airfall.  
 643



644 **Figure 9.** (a) Sketch map of inferred material transport direction (arrows) in the Soii crater region  
 645 after Malaska et al. (2016b), published in Figure 8 in Schoenfeld et al. (2023), with valleys and  
 646 channels (blue lines), craters (red), and putative craters (black). (b) Material transport direction on  
 647 top of the compositional map (color legend in Figure 7b).  
 648  
 649

650 *Fluvial, Aeolian, and Lacustrine Processes:* Two significant units found in the Soii crater  
 651 region, the bright gradational plains (*phg*) and the bright streak-like plains (*psh*), are proposed to  
 652 be two endmembers of the same type of fundamental deposit, reflecting either dominantly fluvial  
 653 or aeolian transport, respectively (Schoenfeld et al., 2023). These aeolian and fluvial origin  
 654 assumptions are based on geomorphological results from SAR data as presented in Schoenfeld et  
 655 al. (2013). According to the studies by Schoenfeld et al. (2023) and Malaska et al. (2016),  
 656 throughout all the mapping datasets the bright gradational plains and the bright streak-like plains  
 657 have both very similar signatures (bright), diffuse internal texture, and comparable microwave  
 658 emissivity. The elongated nature of *psh* with directions parallel to adjacent linear dunes suggests  
 659 aeolian origin for *psh*, while the *phg* units appear as broad plains originating from alluvial fans and  
 660 channels. The RT results from the analysis of VIMS data are consistent with these proposed  
 661 interpretations with regards to their origin (Sections 3.3, 3.4; Figure 4), since in the very top layer  
 662 of their surfaces, *phg* is one of the lowest in albedo, which could be consistent with fluvial origin  
 663 with a surface dampened by liquids. Meanwhile, *psh* is particularly bright at all wavelengths,  
 664 interpreted as an aeolian deposit with a lack of ponded liquids. As a result the high in albedo values

665 (bright) *psh* are associated with a dry surface, while the low in albedo values (dark) *pgl* with a wet  
666 surface. Radiometry data are inconclusive (*pgl*: 0.92-0.93 and *psh*: 0.94-0.96).

667 *Lacustrine Processes*: There are 60 features within the Soi crater region consistent with the  
668 morphology and size of the sharp-edged depressions (*bse*) of the north pole (Schoenfeld et al.,  
669 2023). In addition, two plains units, the scalloped plains (*psv*) (spectrally analysed in Solomonidou  
670 et al., 2018) and the dark irregular plains (*pil*), which are only been found in the midlatitude zone  
671 of Titan, are found adjacent to the SEDs (Schoenfeld et al., 2023).

672 As noted in Malaska et al. (2016a) and Lopes et al. (2020) both units play an important role  
673 in the definition of the mid-to-pole transitional zones and due to morphological and microwave  
674 emissivity measurements it is suggested that the *psv* is a unit with a thick organic layer much like  
675 the undifferentiated plains (Schoenfeld et al., 2021), with which the spectral analysis agrees,  
676 suggesting an organic nature with the dark material being dominant (Fig. 6). However,  
677 compositional analysis of the *psv* unit suggests that the second most abundant material in the  
678 optical surface is water-ice. We propose that this material is mostly organics at depth (consistent  
679 with microwave emissivity), but with an optical coating on the top consistent with spectral  
680 analysis, which is the opposite of what seems to occur at the Xanadu part of the Soi crater region.  
681 As discussed earlier, temporal analysis reveals an interesting temporal albedo change, with two  
682 particular *psv* becoming more abundant in dark material in 2014 (T97) than they were in 2007  
683 (T25) and 2013 (T94) (Solomonidou et al., 2016; 2018). All *pil* and *bse* share similar estimated  
684 compositions with *psv* having dark material and water-ice mainly in the mixtures of their top layer.

#### 685 4.2 Correlation of morphology and composition

686 We have analyzed the Soi crater region and identified various combinations of mixed  
687 materials in the top layer of the surfaces of the 22 geomorphological units, including organics,  
688 methane, and water-ice.

689 Our compositional mapping provides a glimpse into the compositional evolution of Titan.  
690 Similar to lower equatorial regions, we find abundant dark material to be the major constituent of  
691 a mid to high-latitude region ( $>40^{\circ}\text{N}$ , Fig. 7a). This is also the area where scalloped plains are  
692 ‘hosting’ the midlatitude SEDs and the dark irregular plains ( $40\text{-}60^{\circ}\text{N}$ ,  $140\text{-}170^{\circ}\text{W}$ ). In addition,  
693 methane-like (simple organics) spectral features are found widespread in the Soi crater region. The  
694 high emissivity results consistent with organic materials agree with the constraints put by the  
695 VIMS results except for two units: the dark irregular plains and the streak-like plains and the  
696 Xanadu region included in the Soi crater region, suggesting compositional differences in the  $\mu\text{m}$   
697 to cm layers.

698 In early VIMS studies, the major spectral “bright” units were found to generally correspond  
699 to mountains and elevated areas in radar (Barnes et al., 2007). Our results from the Soi crater  
700 region show that there is a significant amount of tholins that appears to be covering the top layers  
701 of the hummocky and mountainous terrains at the low latitudes (Fig. 7a), even though the vast  
702 majority of the low latitudes of the Soi region is covered with the dark organic material. Notably,  
703 another group of hummocky terrains is located in the midlatitudes ( $30\text{-}50^{\circ}\text{N}$ ) of the Soi crater  
704 region and consists mainly of water-ice with a secondary component of tholins. One common  
705 characteristic of all highland terrains is that they all appear to have tholins in their mixtures in  
706 significant amounts and/or significant amounts of  $\text{H}_2\text{O}$  ice. In addition, the percentage of methane-  
707 like materials (simple organics – aliphatic hydrocarbons) in top surfaces found at higher latitudes  
708 is larger than those found at lower latitudes (Table 3). Exposed crater rims show a mixture of only  
709 water-ice and tholins, suggesting that after the impact revealed water-ice (Crosta et al., 2021), it

710 was then coated in tholin, but not dark material. However, some highland areas that are exposed  
711 to significant fluxes of dune material also show dark material present, while those more protected  
712 appear to have less dark material present. In Solomonidou et al. (2018) the  
713 hummocky/mountainous units (all located near the equator and 210-245°W) were among the  
714 darkest, while in the Soi crater region they are the brightest in the short wavelengths suggesting  
715 some combination of materials that made them very bright at the short wavelength, which we  
716 attribute to increased tholin presence. The labyrinth terrains, even though they only appear in the  
717 Soi region at a specific location at around 50°N and represent only ~0.4% of the entire Soi crater  
718 region, spectrally look very similar to the ones analyzed in Solomonidou et al. (2018), namely  
719 Junction, Tleilax, and Richese and those in Malaska et al. (2020). The Soi region labyrinths are  
720 spectrally very similar to the undivided plain materials (*pu*), in both derived RT VIMS and  
721 microwave emissivity. They are both consistent with a surface of tholins and water-ice with bulk  
722 suggesting mostly organics.

723 Most craters with the Soi crater region appear to be almost entirely buried under organic  
724 material. The ones close to the equator lack any water-ice and are predominantly organic-rich,  
725 while the Soi crater rim and ejecta are rich with tholins, followed by water-ice, as also suggested  
726 in Solomonidou et al. (2020a).

727 The undivided dark plains (*pdu*) present some of the highest estimated percent abundances  
728 of water-ice within the Soi crater region, along with the hummocky/mountainous terrains. There  
729 are, however, three *pdu* high latitude exposures rich in the dark material mixed with water-ice.  
730 These differences of the optical surface between the different locations of the same unit suggest  
731 that either aeolian or fluvial activity removed part of the optically thin coat of the surface and  
732 revealed underlying, possibly wet material. Similarly, the absence of the dark organic material in  
733 the undivided plains (*pu*) could be attributed to aeolian and/or fluvial processes that have removed  
734 these materials from the visible surface.

735 Finally, most cases of the featureless sand sheets unit (*ds*), which only appear over 15°N,  
736 appear to be midway in composition between dune sands and midlatitude plains. That is, relative  
737 to the dunes, the sand sheet material has less dark material, but more tholin material. This is in  
738 contrast to the nature of the linear dunes (*dl*) of the Soi crater region, which are very consistent  
739 with having a dark organic composition, at least on the top surface. The featureless nature of *ds*  
740 and the fact that the tholins are often secondary suggests either an addition of tholin material to  
741 change the relative percentage, or a removal of dark materials. The generic results on the dune unit  
742 agree with the organic and less water ice nature of the VIMS ‘brown’ unit that corresponds to the  
743 dunes as per previous studies (Barnes et al., 2007; Soderblom et al., 2007).

744 Previous studies have highlighted a notable correlation between the chemical composition  
745 of the thin layer covering Titan's surface, as observed by VIMS (with a thickness on the order of  
746 micrometers), and latitude (Lopes et al., 2016; Malaska et al., 2016; Solomonidou et al., 2018;  
747 2020a). While there are instances where geomorphology and composition coincide, such as the  
748 distinct 'icy' undivided hummocky terrains (*hu*) within the expansive undivided plains (*pu*) of  
749 organic origin at midlatitudes, the influence of latitude, as well as aeolian and fluvial processes,  
750 appears to exert significant control over the surface material comprising the thin top layer.

#### 751 4.3 Interpreted geologic history

752 The Soi crater region has the typical geomorphology of most of Titan's surface. It contains  
753 plains, dunes, and mountainous terrains (Malaska et al., 2016a; Lopes et al., 2020; Schoenfeld et  
754 al., 2021; 2023) and a latitudinal dependence in chemical composition revealing almost complete



755 coverage of organic material in the equatorial regions and a surface expression of water-ice in the  
756 midlatitudes (Solomonidou et al., 2018; 2020b). However, at the higher latitudes a different  
757 geologic history is apparent for the Soi crater region.

758 The presence of dry lakes into the midlatitudes as low as 40°S supports the hypothesis that  
759 Titan had a wetter climate in the past (e.g., Moore et al., 2014). At these midlatitudes, scalloped  
760 plains and dark irregular plains have been identified (Schoenfeld et al., 2023) adjacent to the SEDs;  
761 this plain/lake northern area is one of the most interesting parts of the Soi region given that it is  
762 the first time that the dark organic material has been identified in abundance in a mid-to-high  
763 latitude area in the VIMS RT analysis (Fig. 7a).

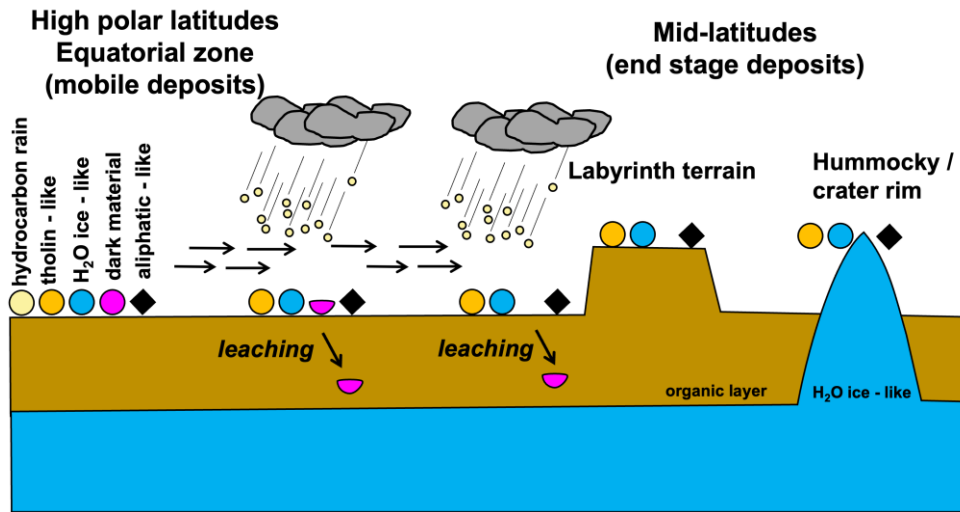
764 Our results show that the areas around latitude 35°N are dominated by surface spectral  
765 responses typical of tholin materials, with ice-like materials and dark materials as minor  
766 components. Compared to the lower latitudes, there is an enhanced presence of aliphatic  
767 hydrocarbon-like materials (methane) in the midlatitudes, while in the higher latitudes, there is an  
768 even greater presence. Our compositional analysis is consistent with a gradation of aliphatic  
769 hydrocarbon materials being low at the equator, and increasing in relative percentage at higher  
770 latitudes (e.g., Mitchell, 2008; Rannou et al., 2006; Tokano et al., 2005; Faulk et al., 2017). The  
771 equatorial regions and high midlatitude plains units both contain elevated amounts of dark  
772 materials with a lower amount of tholin material when compared to the midlatitude plains units.

773 From arguments presented in Malaska et al. (2016b) on material transport, Titan's  
774 midlatitude regions appear to be areas fed from converging material coming from high latitudes  
775 towards the SE, and from equatorial areas towards the NE. This suggests that the midlatitude  
776 regions are composed of end stage of Titan windblown deposited materials that have since been  
777 subjected to rainfall and perhaps other aging processes. We find that materials at these convergent  
778 latitudes are spectrally similar to tholin-like materials and water ice-like materials. In order to  
779 convert dune materials and polar plains materials to midlatitude materials requires either removing  
780 the dark material component, or adding additional tholin components.

781 Addition could be due to density-selective transport, if we assume that all three materials  
782 have differing densities and/or material properties. For fluvially transported materials, large-scale  
783 storms (Faulk et al., 2017) have the potential to transport significant quantities of sediment as  
784 overbank deposits. If the tholins and water-ice materials are particularly buoyant compared to the  
785 dark materials, then floodplains should lack any significant dark material components. With  
786 greater spatial resolution, we would therefore expect floodplains to have a decreasing dark material  
787 component away from any given channel. Previous authors have noted the lack of channels in the  
788 midlatitude plains (Miller et al., 2021), although there may be effects that obscure the radar  
789 signature. In contrast, aeolian processes may transport all three types of sedimentary materials at  
790 any given time. To explain the dearth of dark materials at the convergent latitudes, we therefore  
791 require that such materials simply do not get deposited there. This could be due to either physical  
792 or chemical breakdown over short transport distances, or that the dark materials are denser than  
793 the other two sedimentary materials and get left behind due to density-selective transport. In this  
794 scenario, we postulate that dark materials may be denser and/or weaker, with both fluvial and  
795 aeolian mechanisms acting to sort Titan's different sedimentary materials. This would be  
796 analogous to size-selective transport on Earth, except with density playing the role in giving rise  
797 to uniquely separated deposits of sedimentary materials.

798 An alternative possibility is the removal of the dark organic component from the material  
799 deposited at the convergent latitudes. Tholin materials and water-ice materials are both predicted  
800 to be among the least soluble materials on Titan and would theoretically form a remnant lag

801 deposit, as more soluble materials, which could possibly include the dark materials, were leached  
 802 away into the subsurface by occasional rainfall. Leaching in geology corresponds to loss of soluble  
 803 substances from the top layer of the surface by percolating precipitation. Dark materials are present  
 804 in deposits to the N and in dune materials in the S in the Soi crater region. Since the dark materials  
 805 are present in presumably wetter polar deposits, we postulate that some of the dark materials may  
 806 be sourced there (possibly involving lakes or fluvial activity), while the midlatitudes create a  
 807 “sink” for these materials. We thus present an alternative compositional evolution cycle where  
 808 grains and materials coated in dark materials are delivered through aeolian transport into the  
 809 deposition belts and subjected to extensive leaching which dissolves the dark materials and allows  
 810 those dissolved materials to percolate into the deep subsurface, thus creating remnant optical  
 811 surface lag of insoluble materials rich in either water-ice or tholins (Fig. 10). This implies that  
 812 grains coated in dark materials are more recently formed and have not had their dark material  
 813 coatings removed. This also implies that dark material would be sourced at high latitudes (for  
 814 northern polar regions) and at low latitudes (for equatorial dunes).  
 815



816  
 817 **Figure 10.** Scheme showing midlatitude leaching of dark material from episodic rainfall on Titan.  
 818

819 Older exposed terrains thus should also be composed of tholins and water-ice materials, as  
 820 long as they are not receiving new dark material inputs. Thus, the mountains in the SE section of  
 821 Figure 7c, which is part of the extreme part of Northern Xanadu, appear to be ‘protected’ from  
 822 dark material deposition, or, most likely that removal process of the dark material have proceeded  
 823 quicker than overall deposition. Overall, we envision a scenario as shown in Figure 10, where  
 824 mobile materials contain dark material, that becomes leached, likely from episodic rainfall, as it  
 825 arrives to its end-stage destination in the midlatitudes. This scenario as pictured also is supported  
 826 by microwave emissivity data, which probes deeper. While end stage surface lag composed of  
 827 tholins coats labyrinth, mountain, and plains almost equally, the deeper probing microwave  
 828 emissivity can discriminate between hummocky and mountain materials composed of water-ice,  
 829 and scalloped/undifferentiated plains and labyrinths composed of organic materials.  
 830

## 831 **5 Conclusion**

832 The SoI crater region is an important Titan region as it represents the transition between  
833 the equatorial, the midlatitudes, and the high-altitudes of the northern hemisphere of Titan. Our  
834 analysis developed a working hypothesis for the formation and evolution of the SoI crater region  
835 through the combination of the geomorphological mapping performed by Schoenfeld et al. (2023)  
836 and compositional mapping and radiative transfer analysis performed here. Our work suggests  
837 propable relationships between the dunes (source), scalloped plains (source), and undifferentiated  
838 plains (sink) and brings together and explains the differences in nature of the top layers of the  
839 surface from infrared spectra and microwave emissivity measurements. It also infers the geological  
840 processes and relationships responsible for their formation and evolution. We suggest that the dark  
841 material is a mobile unit that indicates “young” terrains and compositions, while tholin/water-ice  
842 mixtures that dominate areas around latitude 35°N show a material that is older and closer to end  
843 stage aeolian plain deposits. This suggests that Titan’s compositional evolution cycle includes  
844 aeolian transport and leaching. These results provide a better understanding of the geologic  
845 processes that govern Titan’s surface and will help enhance the science return of future missions  
846 such as Dragonfly, and other mission concepts (e.g., Tobie et al., 2014; Lorenz et al., 2021; Barnes  
847 et al., 2021; Sulaiman et al., 2021; Rodriguez et al., 2022).

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## 863 **Open Research**

864 All *Cassini* data used in this article can be accessed in the Planetary Data Systems (PDS), PDS  
865 Image Atlas ( [for  
866 VIMS and \(\[\\) RADAR. The detailed product IDs for VIMS can be found in Table 2. The  
867 spectral library databases can be accessed here: <http://ghosst.osug.fr>. Full descriptions of the  
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873\]\(https://pds-imaging.jpl.nasa.gov/search/?fq=ATLAS\_MISSION\_NAME%3Acassini&fq=TARGET%3Atitan&fq=-ATLAS\_THUMBNAIL\_URL%3Abrwsnotavail.jpg&fq=ATLAS\_INSTRUMENT\_NAME%3Aradar&q=%3A\*\)](https://pds-imaging.jpl.nasa.gov/search/?fq=-ATLAS_THUMBNAIL_URL%3Abrwsnotavail.jpg&fq=ATLAS_MISSION_NAME%3Acassini&fq=ATLAS_INSTRUMENT_NAME%3Avims&fq=TARGET%3Atitan&q=%3A*)

874 radiative transfer model are provided by Hirtzig et al., (2013)  
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876 Imaging and Analysis software ([https://www.l3harrisgeospatial.com/Software-](https://www.l3harrisgeospatial.com/Software-Technology/ENVI)  
877 [Technology/ENVI](https://www.l3harrisgeospatial.com/Software-Technology/ENVI)) and the Interactive Data Language (IDL), both provided by L3Harris  
878 Geospatial.

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1237 **Appendix**

1238

1239 **Table 3.** Compositional constraints of the various units (261 locations) within the Soi crater region.  
1240 The various locations are shown in Figure 4. The mixtures are given by percentages of different  
1241 constituents (H<sub>2</sub>O, CH<sub>4</sub>, tholins, and dark organic material). HC<sub>3</sub>N, CO<sub>2</sub>, NH<sub>3</sub> ices were not  
1242 detected in these locations. Spectra in full resolution for all presented constituents can be found in  
1243 Figure 3.

Items	Location	Unit	Dark	H <sub>2</sub> O ice	Tholins %	CH <sub>4</sub> %
1.	8	<i>pul</i>	40	10	45	5
2.	8b	<i>pul</i>	60	-	40	-
3.	14	<i>pul</i>	60	-	45	-
4.	24b	<i>pul</i>	20	30	40	10
5.	29	<i>pul</i>	-	40	40	20
6.	41	<i>pul</i>	-	50	25	25
7.	44	<i>pul</i>	50	30	10	10
8.	52	<i>pul</i>	-	20	80	-
9.	53b	<i>pul</i>	-	25	60	15
10.	55b	<i>pul</i>	35	15	30	20
11.	56	<i>pul</i>	-	25	60	15
12.	58b	<i>pul</i>	-	45	35	10
13.	63	<i>pul</i>	-	50	40	10
14.	73c	<i>pul</i>	20	25	40	15
15.	79	<i>pul</i>	-	25	60	15
16.	80b	<i>pul</i>	-	40	60	-
17.	98b	<i>pul</i>	-	45	35	20
18.	101	<i>pul</i>	-	45	50	5
19.	101b	<i>pul</i>	-	45	50	5
20.	102b	<i>pul</i>	-	50	45	5
21.	105	<i>pul</i>	-	40	55	5
22.	106	<i>pul</i>	-	30	65	5
23.	108c	<i>pul</i>	-	30	50	20
24.	A3	<i>pul</i>	50	25	15	10
25.	A4	<i>pul</i>	65	20	10	5
26.	A6	<i>pul</i>	60	35	-	5
27.	A13	<i>pul</i>	60	30	-	10
28.	A13c	<i>pul</i>	60	30	-	10
29.	A18b	<i>pul</i>	-	35	50	15
30.	A20	<i>pul</i>	-	50	30	20
31.	A22	<i>pul</i>	-	30	50	20
32.	6b	<i>pfv</i>	60	15	25	-
33.	8c	<i>pfv</i>	50	-	45	5
34.	9c	<i>pfv</i>	40	-	55	5
35.	10	<i>pfv</i>	35	10	50	5
36.	10c	<i>pfv</i>	60	-	40	-
37.	11b	<i>pfv</i>	60	25	15	-
38.	12	<i>pfv</i>	60	-	40	-
39.	21	<i>pfv</i>	-	25	65	10
40.	22b	<i>pfv</i>	35	-	50	10
41.	23	<i>pfv</i>	70	20	-	10
42.	27b	<i>pfv</i>	40	-	60	-
43.	34	<i>pfv</i>	45	30	10	15
44.	35	<i>pfv</i>	5	25	55	15
45.	35b	<i>pfv</i>	5	25	55	15
46.	44b	<i>pfv</i>	15	40	30	15
47.	53c	<i>pfv</i>	15	30	40	15
48.	56b	<i>pfv</i>	-	45	40	15
49.	58c	<i>pfv</i>	-	45	35	10
50.	60	<i>pfv</i>	-	55	45	-
51.	60b	<i>pfv</i>	-	55	45	-
52.	67	<i>pfv</i>	75	-	25	-
53.	70	<i>pfv</i>	60	25	10	5
54.	73	<i>pfv</i>	-	50	50	-
55.	75	<i>pfv</i>	-	40	60	-
56.	75b	<i>pfv</i>	-	40	60	-

57.	77b	<i>pfv</i>	50	30	20	-
58.	79b	<i>pfv</i>	-	25	60	15
59.	97	<i>pfv</i>	50	30	-	20
60.	104	<i>pfv</i>	-	60	35	5
61.	107	<i>pfv</i>	-	40	50	10
62.	108	<i>pfv</i>	-	40	40	20
63.	109b	<i>pfv</i>	-	40	40	20
64.	110	<i>pfv</i>	-	35	60	5
65.	A2b	<i>pfv</i>	60	35	-	5
66.	A13b	<i>pfv</i>	-	30	60	10
67.	A18	<i>pfv</i>	35	-	50	15
68.	A19b	<i>pfv</i>	-	55	45	-
69.	A36	<i>pfv</i>	-	25	70	5
70.	A41	<i>pfv</i>	-	30	65	5
71.	A53	<i>pfv</i>	-	30	65	5
72.	43	<i>psv</i>	45	30	10	15
73.	43b	<i>psv</i>	45	30	10	15
74.	47	<i>psv</i>	40	25	15	20
75.	81	<i>psv</i>	35	25	20	20
76.	87	<i>psv</i>	40	20	20	20
77.	87b	<i>psv</i>	40	25	20	15
78.	50	<i>pil</i>	-	25	55	20
79.	82	<i>pil</i>	45	30	15	10
80.	84b	<i>pil</i>	20	25	35	20
81.	94	<i>pil</i>	30	25	25	20
82.	94b	<i>pil</i>	25	25	30	20
83.	95	<i>pil</i>	55	25	-	20
84.	96	<i>pil</i>	50	30	5	15
85.	97b	<i>pil</i>	50	30	5	15
86.	98	<i>pil</i>	-	45	35	20
87.	98c	<i>pil</i>	-	45	35	20
88.	55	<i>psh</i>	35	15	30	20
89.	61	<i>psh</i>	-	50	50	-
90.	80	<i>psh</i>	-	40	60	-
91.	100	<i>psh</i>	-	35	55	10
92.	77	<i>pgh</i>	55	20	25	-
93.	78	<i>pgh</i>	55	20	25	-
94.	A10b	<i>pgh</i>	55	20	25	-
95.	4	<i>pu</i>	40	5	50	5
96.	5	<i>pu</i>	30	10	55	5
97.	7	<i>pu</i>	45	5	45	5
98.	30b	<i>pu</i>	5	30	40	25
99.	31b	<i>pu</i>	5	30	40	25
100.	33	<i>pu</i>	10	25	40	25
101.	36	<i>pu</i>	-	30	45	25
102.	36b	<i>pu</i>	-	30	45	25
103.	39b	<i>pu</i>	25	65	-	10
104.	40	<i>pu</i>	-	40	45	15
105.	40b	<i>pu</i>	-	40	45	15
106.	41c	<i>pu</i>	-	45	30	25
107.	42	<i>pu</i>	35	35	-	30
108.	45	<i>pu</i>	10	40	30	20
109.	45b	<i>pu</i>	-	20	60	20
110.	46	<i>pu</i>	30	25	30	15
111.	46b	<i>pu</i>	40	15	30	15
112.	48	<i>pu</i>	-	20	60	20
113.	57	<i>pu</i>	-	35	60	5

114.	59	<i>pu</i>	-	45	40	15
115.	62	<i>pu</i>	-	35	40	25
116.	64	<i>pu</i>	-	35	40	25
117.	65	<i>pu</i>	-	50	35	15
118.	72	<i>pu</i>	-	35	55	10
119.	74	<i>pu</i>	-	40	55	5
120.	76	<i>pu</i>	-	40	35	25
121.	89	<i>pu</i>	-	40	55	5
122.	90	<i>pu</i>	-	50	50	-
123.	90b	<i>pu</i>	-	40	55	5
124.	91	<i>pu</i>	-	25	60	15
125.	93	<i>pu</i>	-	35	60	5
126.	99b	<i>pu</i>	-	60	30	10
127.	106b	<i>pu</i>	-	30	65	5
128.	111	<i>pu</i>	-	35	60	5
129.	A10	<i>pu</i>	40	-	50	10
130.	30	<b><i>pdu</i></b>	25	40	25	10
131.	31	<i>pdu</i>	25	35	30	10
132.	32	<i>pdu</i>	15	35	35	15
133.	32b	<i>pdu</i>	15	40	30	15
134.	33b	<i>pdu</i>	15	40	30	15
135.	37	<i>pdu</i>	15	40	40	5
136.	37b	<i>pdu</i>	10	45	40	5
137.	38	<i>pdu</i>	25	40	20	15
138.	38b	<i>pdu</i>	25	40	20	15
139.	39	<i>pdu</i>	-	65	25	10
140.	42b	<i>pdu</i>	40	25	20	15
141.	48b	<i>pdu</i>	40	25	20	15
142.	49	<i>pdu</i>	35	25	25	15
143.	49b	<i>pdu</i>	30	25	30	15
144.	104b	<i>pdu</i>	-	60	35	5
145.	A15	<i>pdu</i>	-	50	40	10
146.	A15b	<i>pdu</i>	-	50	40	10
147.	A19c	<i>pdu</i>	-	55	45	-
148.	9b	<b><i>ds</i></b>	60	25	-	15
149.	19c	<i>ds</i>	60	25	-	15
150.	21b	<i>ds</i>	10	20	60	10
151.	22	<i>ds</i>	10	20	55	15
152.	24	<i>ds</i>	50	30	-	20
153.	25	<i>ds</i>	60	25	-	15
154.	27	<i>ds</i>	65	35	-	-
155.	51	<i>ds</i>	60	-	30	10
156.	54	<i>ds</i>	70	-	30	-
157.	A5	<i>ds</i>	10	30	60	-
158.	A19	<i>ds</i>	-	45	55	-
159.	A31	<i>ds</i>	-	25	60	15
160.	A39	<i>ds</i>	-	25	65	10
161.	A40	<i>ds</i>	10	25	60	5
162.	A47	<i>ds</i>	-	35	60	5
163.	A48	<i>ds</i>	-	35	65	-
164.	A49	<i>ds</i>	-	35	65	-
165.	6	<b><i>dl</i></b>	65	5	30	-
166.	9	<i>dl</i>	75	5	20	-
167.	10b	<i>dl</i>	80	-	20	-
168.	11	<i>dl</i>	85	5	10	-
169.	13	<i>dl</i>	75	-	25	-
170.	15	<i>dl</i>	75	-	25	-

171.	23b	<i>dl</i>	65	-	35	-
172.	28	<i>dl</i>	45	30	15	10
173.	66	<i>dl</i>	75	-	25	-
174.	A1	<i>dl</i>	85	-	10	5
175.	A2	<i>dl</i>	80	15	-	5
176.	A9	<i>dl</i>	70	-	25	5
177.	A12	<i>dl</i>	60	15	20	5
178.	A21b	<i>dl</i>	35	20	25	20
179.	A27	<i>dl</i>	40	25	25	10
180.	A28	<i>dl</i>	40	20	35	5
181.	A34	<i>dl</i>	-	35	60	5
182.	A44	<i>dl</i>	-	30	65	5
183.	A46	<i>dl</i>	-	30	65	5
184.	A52	<i>dl</i>	-	35	65	-
185.	1	<b><i>du</i></b>	70	5	20	5
186.	23e	<i>du</i>	65	-	30	5
187.	26	<i>du</i>	60	-	35	5
188.	57b	<i>du</i>	60	-	30	10
189.	A7	<i>du</i>	70	10	20	-
190.	A13d	<i>du</i>	70	15	25	-
191.	9d	<b><i>hm</i></b>	50	30	20	-
192.	19b	<i>hm</i>	40	-	45	15
193.	41b	<i>hm</i>	-	50	25	25
194.	58	<i>hm</i>	-	35	45	10
195.	77c	<i>hm</i>	50	30	20	-
196.	103b	<i>hm</i>	-	45	50	5
197.	15c	<b><i>hh</i></b>	45	-	55	-
198.	16	<i>hh</i>	-	40	60	-
199.	17	<i>hh</i>	-	25	60	15
200.	17b	<i>hh</i>	-	25	60	15
201.	17c	<i>hh</i>	-	20	65	15
202.	23d	<i>hh</i>	40	-	60	-
203.	53	<i>hh</i>	60	-	40	-
204.	68	<i>hh</i>	55	20	20	5
205.	71	<i>hh</i>	70	30	-	-
206.	73b	<i>hh</i>	40	20	25	15
207.	83	<i>hh</i>	40	25	20	15
208.	102	<i>hh</i>	-	45	50	5
209.	103	<i>hh</i>	-	50	45	5
210.	109	<i>hh</i>	-	50	20	30
211.	A11	<i>hh</i>	20	20	55	5
212.	A14	<i>hh</i>	15	40	45	-
213.	A32	<i>hh</i>	-	25	65	10
214.	A33	<i>hh</i>	-	25	60	15
215.	A20b	<i>hh</i>	-	45	35	20
216.	A21	<i>hh</i>	25	25	35	15
217.	A24	<i>hh</i>	-	25	65	10
218.	A25	<i>hh</i>	-	25	60	15
219.	A37	<i>hh</i>	-	30	65	5
220.	A38	<i>hh</i>	-	30	65	5
221.	A50	<i>hh</i>	-	40	60	-
222.	A51	<i>hh</i>	-	30	60	10
223.	A54	<i>hh</i>	-	30	65	5
224.	A55	<i>hh</i>	-	35	60	5
225.	2	<b><i>hu</i></b>	10	25	60	5
226.	3	<i>hu</i>	50	15	35	-
227.	18	<i>hu</i>	40	-	45	15



228.	18b	<i>hu</i>	40	-	45	15
229.	19	<i>hu</i>	-	25	65	10
230.	20	<i>hu</i>	40	-	45	15
231.	64b	<i>hu</i>	-	65	35	-
232.	92	<i>hu</i>	-	65	35	-
233.	99	<i>hu</i>	-	65	20	15
234.	99c	<i>hu</i>	-	65	20	15
235.	108b	<i>hu</i>	-	40	40	20
236.	A8	<i>hu</i>	55	-	45	-
237.	A16	<i>hu</i>	-	40	60	-
238.	A17	<i>hu</i>	-	35	65	-
239.	15b	<b><i>hph</i></b>	45	-	55	-
240.	A23	<i>hph</i>	-	25	60	15
241.	A26	<i>hph</i>	-	30	65	5
242.	A29	<i>hph</i>	-	25	65	10
243.	A30	<i>hph</i>	-	30	65	5
244.	A35	<i>hph</i>	-	30	65	5
245.	A42	<i>hph</i>	-	35	60	5
246.	A43	<i>hph</i>	-	35	60	5
247.	A45	<i>hph</i>	-	35	65	-
248.	114	<b><i>lbf</i></b>	20	25	40	15
249.	114b	<i>lbf</i>	20	25	40	15
250.	23c	<b><i>ceh</i></b>	70	-	30	-
251.	52b	<i>ceh</i>		20	80	-
252.	69	<i>ceh</i>	70	-	30	-
253.	52c	<b><i>crh</i></b>		20	80	-
254.	112	<i>crh</i>	-	20	80	-
255.	88	<b><i>cf3</i></b>	70	15	15	-
256.	84	<b><i>bse</i></b>	45	35	-	20
257.	85	<i>bse</i>	35	30	20	15
258.	86	<i>bse</i>	35	30	20	15
259.	113	<i>bse</i>	25	20	35	20
260.	115	<b><i>brh</i></b>	20	25	40	15
261.	116	<i>brh</i>	40	25	20	15

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