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A complex subglacial water system below the South Pole of Mars unveiled by new MARSIS data

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Abstract

The recent detection of a body of liquid water at the base of the Martian South Polar Layered Deposits (SPLD) by the Mars Radar for Subsurface and Ionospheric Sounding (MARSIS) has reinvigorated the debate about the origin and stability of liquid water under present-day Martian conditions. To further explore the study area (Ultima Scopuli) and investigate the possible nature and extent of the water, we acquired new radar data to provide a denser coverage of the area relative to the earlier study. We analysed the complete MARSIS dataset acquired over the region using signal processing procedures commonly applied on Earth to discriminate between wet and dry subglacial areas. The results of this new study independently corroborate the previous detection of a significant basal body of liquid water at the base of Ultima Scopuli and provide evidence for other wet areas in its surroundings, suggesting a complex hydrologic network deserving of further investigation. Here we also suggest that the subglacial water is likely to be hypersaline perchlorate brines, which are known to form at the

polar regions of Mars and have been shown to survive for geologically significant periods of time at temperatures far below their eutectic values.

Orbiting subsurface radar sounders are powerful geophysical tools to investigate a planetary crust at shallow depths. This technique employs a burst of radio waves to image the buried geological structures in a similar fashion to active seismic prospection. As radio waves propagate with little attenuation in ice, this method is particularly well suited to study the internal structure of the Martian Polar Layer Deposits (PLDs)¹ and to detect the bedrock below such deposits². The possible identification of subsurface liquid water was one of the main goals to develop MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding), a radar sounder similar to those used on Earth to search for subglacial water³. The sounder was launched in 2003 onboard the Mars Express spacecraft and began to collect data in the summer of 2005. After several years of data acquisition, however, the lack of any clear evidence of basal liquid water below the Martian Polar Caps started to challenge the original hypothesis⁴, suggesting that water, if present, may be located at a greater depth than previously thought^{5,6}. The recent radar detection by Orosei et al.⁷ of subglacial liquid water in Ultima Scopuli, at the base of the South Polar Layered Deposits (SPLDs), reignited the scientific debate about present-day stability of liquid water at the Martian poles. The discovery was based on the analysis of 29 radar profiles collected by MARSIS over a 200x200 km² area centered at 193°E 81°S, with the ratio between basal and surface echo intensity highlighting two distinct areas, one bright and one non-bright. Using a robust probabilistic approach⁸ two different probability density functions of the basal permittivity were retrieved, from which wet (bright) and dry (not-bright) basal conditions were determined. Because the nature of the body of liquid water detected by MARSIS was not addressed in detail in Orosei et al.'s paper⁷, in the present work we extend our investigation to constrain and define the characteristics and spatial distribution of the subglacial bright areas associated with basal liquid water and we discuss possible physical and chemical conditions to explain formation and persistence of such water at the Martian south polar regions. We increased the area coverage with 105 new MARSIS observations and applied a methodological approach adapted from signal processing procedures commonly used in terrestrial radar sounding to discriminate between wet and dry sub-glacial basal conditions. This approach strongly improves our capability to identify water body candidates and test the reliability of their detection, enabling us to localize the position and extent of several subglacial bodies of liquid water, in addition to that found by Orosei et al.⁷. These findings confirm Orosei et al.'s⁷ discovery, and further highlight a complex hydrology for the SPLDs at Ultima Scopuli.

Presently Mars is a cold hyper-arid desert, but it may not have always been so. The geological record clearly demonstrates that the climate has undergone dramatic changes throughout Mars's planetary history, even though our understanding of the processes responsible for such evidence is still incomplete. Geological, morphological and compositional data from Late Noachian to Early Hesperian (~3.7 Ga) terrains⁹⁻¹⁴ indicate the past existence of warm and wet periods characterized by temperatures above the freezing point of water, abundant rainfall, and fluvial processes on the surface of Mars. Recently, however, Palumbo et al.¹⁵ and Palumbo and Head¹⁶ have argued that climate models fail to produce global Martian warm and wet periods, and that precipitation was mostly in the form of snow rather than rain. If this is true, direct surface runoff could not have produced a significant morphological signature on the Martian surface. They alternatively proposed that the observed "wet" morphologies on Mars were formed through snow accumulation, snow melting and the resulting secondary runoff.

The transfer of water between the Martian cryolithospheric and atmospheric global reservoirs is linked to the variability of orbital parameters¹⁷, with it being generally accepted that quasi-periodic variations of orbital eccentricity¹⁸ and planetary obliquity¹⁹⁻²² had profound effects on the Martian climate²³. Proof of the effects of orbital forcing on the climate of Mars is evident in the stratigraphy of the north polar layered deposits (NPLDs), for which there is good correspondence between the timescales of layer deposition and astronomical cycles²¹. The relationship between orbital parameters and the origin, timing and evolution of the layered deposits at the south pole is however still largely unconstrained and problematic^{24,25}, and many more data are needed on the composition and physical properties of the SPLDs to understand the mechanisms for their formation and evolution. It is therefore especially critical to continue expanding the dataset, performing new processing, and broadening the search area started by Orosei et al.⁷. Under present-day climate conditions, the Martian polar caps are generally assumed to be cold-based¹. However, the Late Noachian-Early Hesperian circumpolar Dorsa Argentea Formation displays characteristic esker-like morphologies that have been interpreted as evidence of basal melting under thick ice sheets²⁶, likely made possible by a combination of warmer and wetter climate conditions²⁷ and a significantly higher heat flux (~ 45-60 mW/m²) than at present (20-22 mW/m²)²⁸. Furthermore, ice-sheet structures and km-scale tectonic deformations in the Late Amazonian SPLDs^{29,30} provide evidence of broad ice movement, suggesting localized basal melting of the Martian southern ice sheet under possible warmer conditions³¹.

The set of physical conditions conducive to basal melting at the Martian polar and subpolar regions has been explored by some authors³¹⁻³³ via the theoretical combination of heat flow parameters that could result in ice melting at the base of the south polar ice cap. Recently Sori and Bramson³⁴ suggested that a high geothermal gradient (heat flux ≥ 72 mW/m²) is needed for basal

103 melting of the SPLDs, regardless of the salinity level. The same authors thus postulated that magmatic
104 activity must have occurred in the region less than a million years ago for a liquid water body to exist
105 at the base of the SPLDs. Evidence for late Amazonian (as young as 2 Ma) magmatic activity has
106 been reported in the Elysium region^{35,36}, suggesting the potential for localized high geothermal
107 gradients on Mars in recent geological times. An anomalously high geothermal gradient is, however,
108 not the only possible cause for temperature increases at the base of extensive ice-sheets. For example,
109 localized basal melting of a thick Early Amazonian polythermal ice sheet in Isidis Planitia was
110 modeled by Souček et al.³⁷, who concluded that subglacial wet areas could form under climatic and
111 geologic conditions that are not significantly different from those on present-day Mars.

112 Terrestrial analog studies also indicate that subglacial water reservoirs are common in
113 topographic troughs bound by tectonic structures^{38,39}. Previous radar sounder investigations of the
114 basal interface between the SPLDs and bedrock have found irregular morphologies, characterized by
115 plains, topographic highs and basins at very high latitudes⁴⁰ potentially favorable for the flow and
116 trapping of fluids under the SPLDs. Conversely, the basal topography in the investigated region does
117 not show any appreciable depression (Methods).

118

119 **Radar detection of Martian subglacial water: A lesson from the terrestrial ice-caps**

120 On Earth, Radio-Echo Sounding (RES) represents one of the most valuable methods to detect
121 subglacial bodies of liquid water³. This technique is able to image the internal structure of an ice sheet
122 from surface to bedrock⁴¹. The combination of qualitative (bedrock morphology in the radar image)
123 and quantitative (signal features) analysis leads to the detection of the subglacial water. Historically,
124 four specific criteria have been proposed to identify and categorize the subglacial lakes in East
125 Antarctica⁴²: i) standard deviation of the echo strength (values lower than 3dB indicate that the basal
126 interface is smooth at the scale of the radar footprint); ii) high echo strength relative to the immediate
127 surroundings; iii) absolute echo strength (related to the basal reflection coefficient); and iv) the
128 assumption that a subglacial lake is hydraulically flat^{43,42}. According to such criteria East Antarctic
129 subglacial lakes have been classified as: *definite lakes*, at least partially satisfying all four criteria;
130 *dim lakes*, which satisfy the first two quantitative criteria; *fuzzy lakes*, which only satisfy the absolute
131 and relative signal intensity requirements; *indistinct lakes*, characterized by low standard deviation
132 in echo intensity; and *failing lakes*, that only satisfy one of the four criteria⁴². Recently these criteria
133 have been partially modified and updated to identify more complex subglacial water distribution (e.g.,
134 active lakes)⁴⁴ by using the specularity content related to the angular distribution of the basal
135 scattering^{45,46}. In Greenland, given the paucity of subglacial lakes⁴⁷, RES data have been mainly used
136 to constrain the subglacial basal conditions and to define the spatial distribution of the water

137 (ponded/thawed/frozen) at the ice-sheet bed, mainly using the “pulse peakiness” of the bed echo
138 signal (abruptness or acuity)⁴⁸⁻⁵² and the bed echo intensity variability⁵³. Recently, however, several
139 previously undetected subglacial lakes have been found by applying some of the criteria originally
140 used in East Antarctica⁵⁴. Some of these criteria, together with the specularity content, have also been
141 applied to RES data collected in the Canadian Arctic, resulting in the discovery of the first two
142 isolated hypersaline subglacial lakes on Earth⁵⁵.

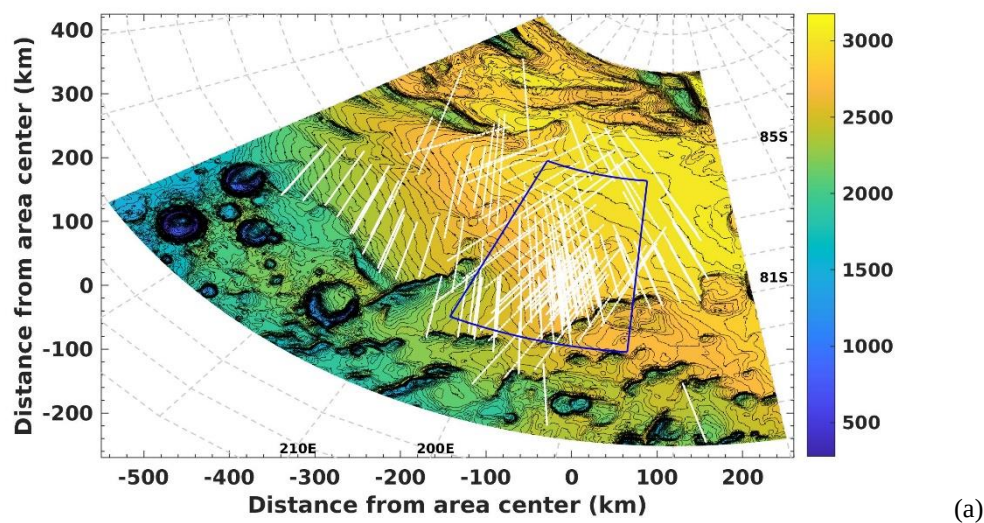
143 MARSIS radar is, in principle, very similar to the systems used in RES investigations,
144 although several aspects limit the number of criteria that can be applied to detect the basal water
145 below the Martian polar caps. Given the operating frequency (1.8-5 MHz), the antenna dimension
146 (40 m) and the altitude of the spacecraft (250-900 km), MARSIS pulse limited radius footprint is very
147 large (from 6 to 11 km) compared to footprints of the common RES radar allocated on airborne
148 platforms and working at higher frequencies (typically of the order of 100m). The bright area below
149 the SPLDs interpreted as a stable body of liquid water⁷ was estimated to be approximately 20 km in
150 extent, i.e., comparable to the dimension of the MARSIS pulse limited footprint. The vertical (~55m
151 in ice) and horizontal (~7km) resolution of MARSIS (Methods) prevents a detailed characterization
152 of the bedrock morphology, topography and hydraulic potential, as the uncertainties associated with
153 the estimation of such parameters are similar in magnitude to the range of measured variations
154 (Supplementary Fig.2). Moreover, as the MARSIS antenna could not be calibrated⁵⁶ and the signal
155 absorption in the SPLDs is not well constrained, the basal reflection coefficient (absolute echo
156 strength) criterion cannot be applied. Given these technical limitations the approach used here to
157 analyze MARSIS data mainly follows the methodology tested in Greenland to discriminate between
158 ponded water and frozen or dry basal conditions. Such a methodological approach is based on signal
159 intensity (which is an indication of the basal reflectivity), signal acuity (which is associated with the
160 smoothness of the bed⁵²) and bed-echo intensity variability (which detects the transition from dry to
161 wet materials at the base of the ice⁵³) (Methods). Note that each parameter has been computed for
162 both surface and basal echoes and then normalized to the median of the relevant surface parameter in
163 order to minimize the effects caused by local surface echo power fluctuations, which are sometimes
164 observed in the data, without altering the along track variation of the basal reflectivity and acuity
165 (Methods).

166 167 168 **New MARSIS data analysis**

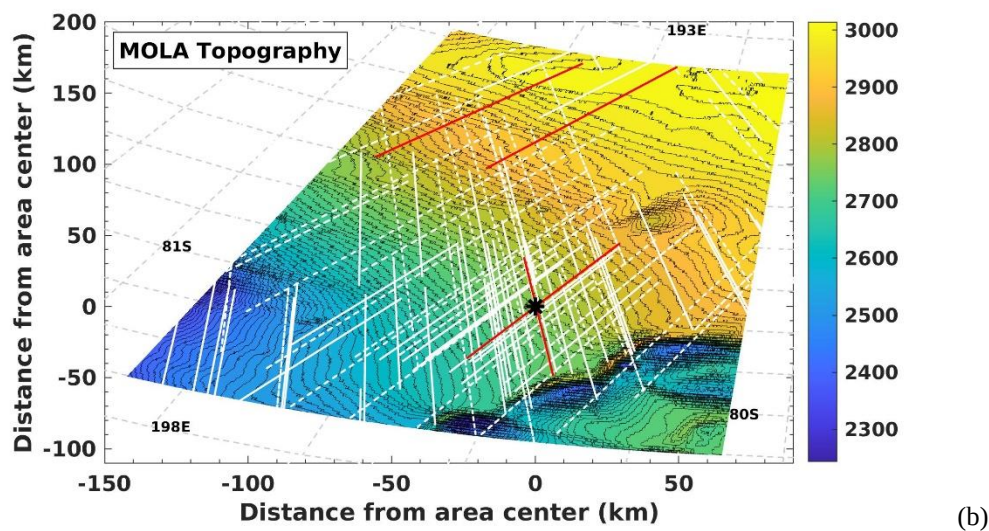
169 The analysis presented in this work was performed on the data acquired in 134 radar profiles
170 during multiple campaigns over Ultima Scopuli from 2010 to 2019 (Figure 1a). We focused on a

171 250x300 km² zone (blue box in Figure 1a), around and including the bright area previously identified
 172 by Orosei et al.⁷, where we have significant data coverage (90 observations) and many radar profiles
 173 that cross each other (Figure 1b). Given the MARSIS pulse length of about 200 m in air, the surface
 174 of the studied area can be considered smooth with elevation gently decreasing northward (Figure 1a).
 175 The basal interface (bottom of the SPLDs) is clearly detectable in all radar profiles and it is thus
 176 possible to estimate the local thickness of the SPLDs under the assumption that the signal velocity
 177 does not change in the entire investigated area. Immediately around the bright area the thickness of
 178 the SPLDs is constant (considering the pulse length and the footprint) but at the regional scale it
 179 progressively decreases in the same direction as the surface (see Figure 2), resulting in an essentially
 180 flat basal topography (Supplementary Fig.2). We acquired data at three MARSIS frequencies: 3, 4
 181 and 5 MHz. The 4MHz dataset was the most complete, and therefore we applied our analysis to this
 182 specific dataset in order to improve the robustness of our statistical analysis. Even if not further
 183 discussed here, we note that the 3 and 5 MHz data and their processing results are consistent with
 184 those obtained from the 4 MHz dataset (Supplementary Fig.1).

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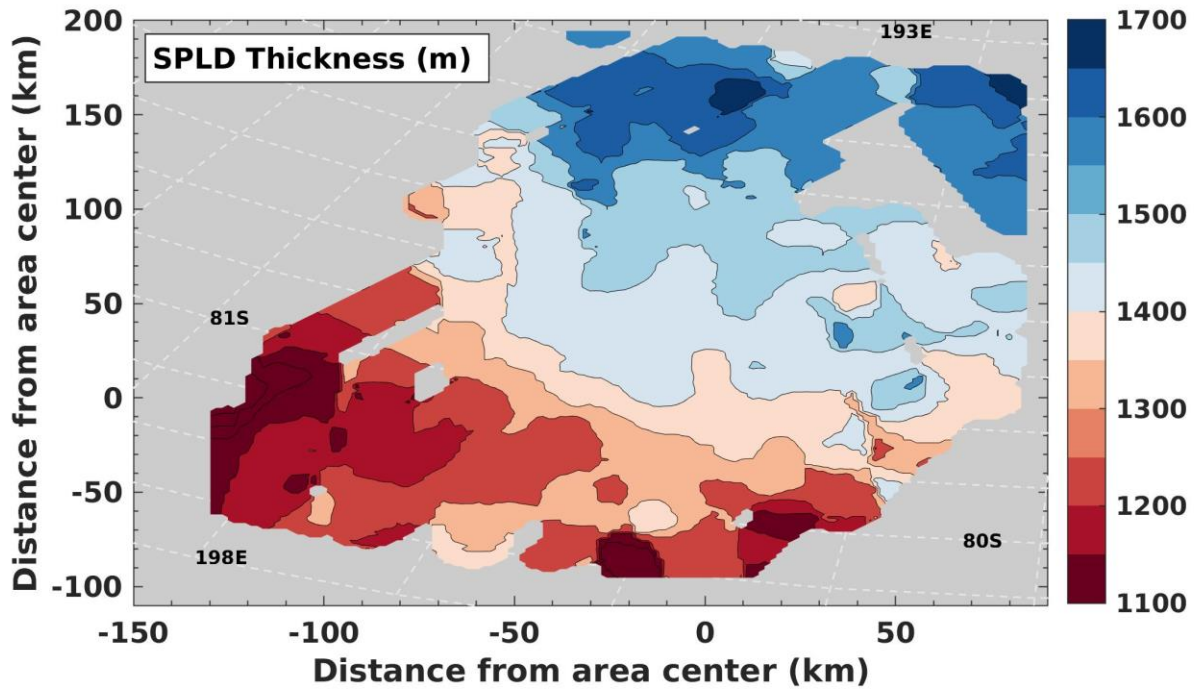


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187 Fig. 1 (a) Ultima Scopuli Mola topographic map and location of MARSIS radar profiles collected in the region. Solid
 188 white lines are Super-frame data and dash white lines are Flash memory data (Methods). Blue box delimits the
 189 investigated area. (b) Detail of the investigated area (the blue box in Fig. 1a). Red lines (observation number 12854,
 190 12861, 10737, 14853) highlight the radar profiles used to describe the three diagnostic parameters (Fig.3) that were
 191 applied to discriminate between wet and dry areas. The black star indicates the center of the bright area detected by Orosei
 192 et al. ⁷ at 193°E and 81°S.

193



194

195 Fig. 2 SPLD thickness computed assuming a velocity value of 163 m/μs ($\epsilon_{ice}=3.4$). Gray areas indicate no data available.

196

197 In order to describe the meaning of the three chosen diagnostic parameters (intensity, acuity and bed-
 198 echo intensity variability) in terms of basal water detection, we selected four representative radar
 199 profiles in the investigated region (red lines in Fig. 1b): two outside (observations 12854 and 12861)
 200 and two across (observations 10737 and 14853) the previously detected bright area . We analyzed the
 201 trend of these parameters along the observations and compared the spatial behavior of each parameter
 202 between observations (see Fig. 3). The surface values of intensity and acuity (black lines in Fig. 3)
 203 are broadly similar in both areas, with limited variations along each observation indicating a smooth
 204 and flat surface at the MARSIS wavelength. Conversely, the basal values (red lines in plots of Fig.
 205 3) are markedly different. In the background area, along orbits 12854 and 12861, basal intensity and
 206 acuity values are constant and much lower than the corresponding surface values, whereas the
 207 intensity variability is always above the surface values. These parameters suggest a low reflectivity
 208 of the basal material (-10 dB relative to the surface), a relatively rough basal interface (low acuity)
 209 and a spatially homogeneous bedrock (relatively constant intensity variability along tracks).

Conversely, the observations acquired across the bright area show a marked increase of the basal intensity (about 10 dB) along track, reaching a maximum value (well above the surface values) at the center of the bright area. Similar trends are observed in the basal acuity values, while intensity variability values change abruptly where the observations approach the bright area. According to Oswald et al.⁵², the occurrence of high intensity and high acuity values in the same location indicates the presence of ponded water, and Jordan et al.⁵³ have shown that intensity variability values exceeding 6 dB mark the transition (edge detector) between dry and wet materials. Moreover, Dowdeswell and Siegert⁵⁷ emphasized that a change in basal intensity of about 10 dB along track could be evidence of the presence of a lake, whereas smaller variations (e.g., on the order of 2dB) could indicate wet sediments or water intruded in the bedrock around a lake⁴². The combination of the three criteria makes the interpretation of the basal conditions along the four profiles quite robust and suggests a remarkable difference in the bed material properties between the two areas: observations 12854, 12861 detected a dry (or frozen) bedrock, whereas observations 10737, 14853 crossed at least one large water ponded area.

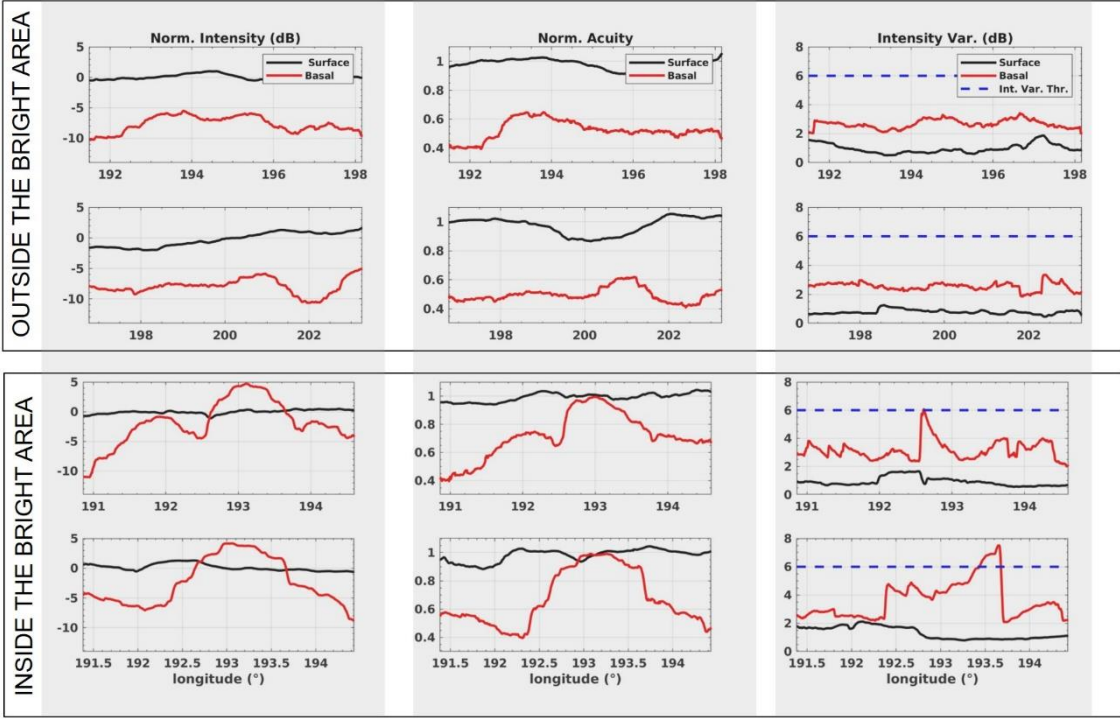
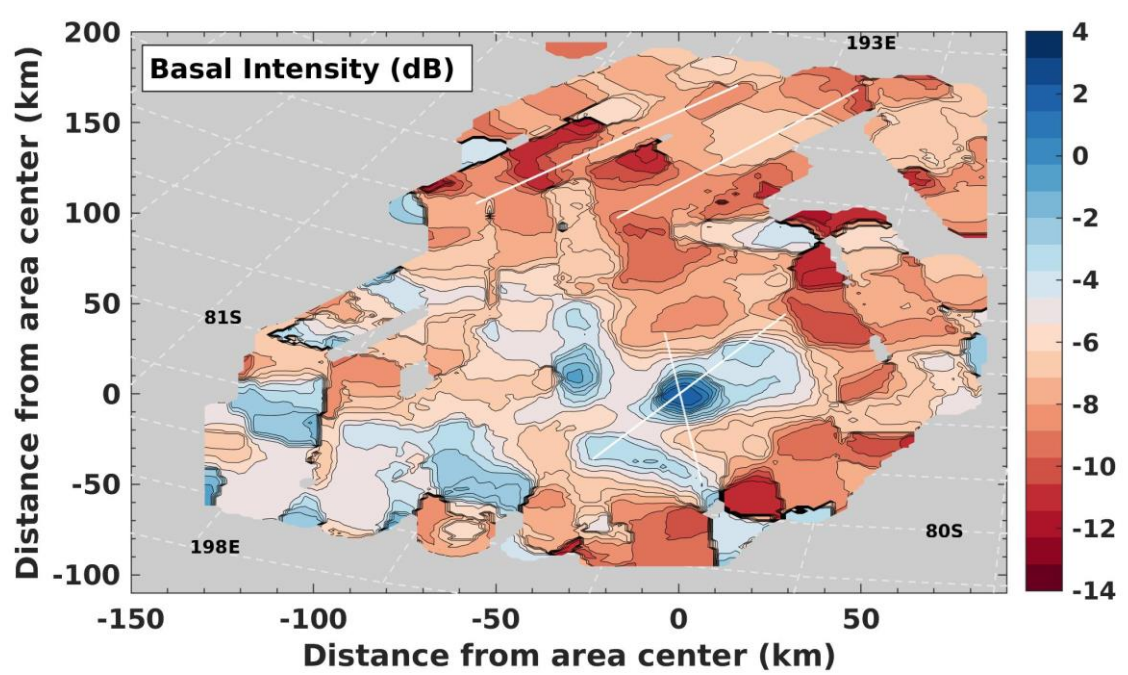


Fig. 3 Data collected outside and inside the bright area. From top to bottom observations are: 12854, 12861, 10737, 14853. Black lines indicate surface and red lines basal parameters. In the right column the dash blue line indicates the water detection threshold (6 dB) according to Jordan et al.⁵³.

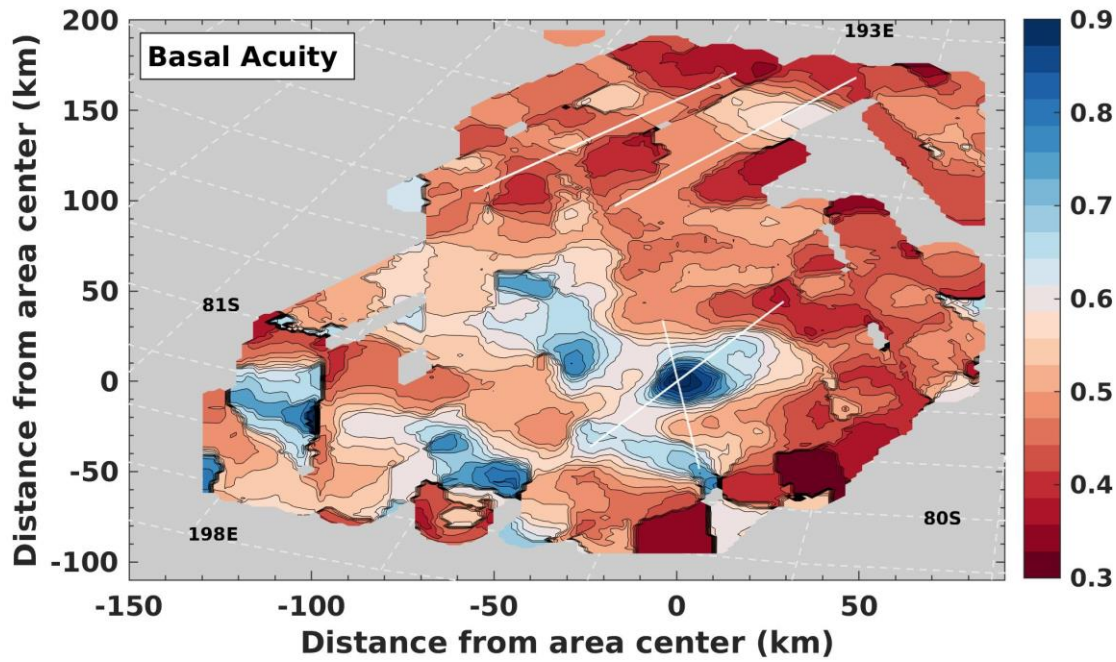
To assess the wet/dry spatial distribution of the basal material below the SPLDs, we used all observations collected in the study area (Fig. 1b) and generated a basal intensity map and a basal acuity map (Fig. 4). Both maps clearly show two distinct areas: an upper southern area characterized

232 by a very low and relatively constant signal intensity [from -14 to -6 dB] and acuity [from 0.3 to 0.6]
 233 and a lower northern area characterized by several patches of high signal intensity [from -3 to 4 dB]
 234 and acuity [from 0.65 to 1]. Comparison of the two maps (Fig. 4) highlights the strong spatial
 235 correlation between the two parameters with only few exceptions, where high values of basal acuity
 236 do not correspond to high values of basal intensity and vice versa. Therefore, following Oswald et
 237 al.⁵², we conclude that the basal material in the southern area is uniformly dry whereas the northern
 238 area is characterized by the presence of several basal patches of ponded water.

239 These results corroborate the initial discovery by Orosei et al.⁷ of a stable body of liquid water
 240 in Ultima Scopuli using a different and independent technique, while at the same time highlighting a
 241 more extensive, complex situation with ubiquitous water patches surrounding the subglacial lake.
 242 This is illustrated through the correlation of the features mapped in Fig. 4 and the plots of the radar
 243 parameters of orbit 10737 (third row in Fig. 3). The trend of basal intensity and acuity in the plots
 244 shows that the ponded area centered at 193°E-81°S (point 0,0 in the maps) is surrounded by other,
 245 weakly spatially constrained wet areas whose distribution is reminiscent of a fuzzy lake, typically
 246 characterized by a large body of water encircled by patchy water pools or wet areas of smaller
 247 extent⁴². This interpretation is also supported by the intensity variability values computed on other
 248 observations partially crossing the lateral water patches (Supplementary Fig.4 and Fig.5). The abrupt
 249 transitions in bed material properties are still well detectable, however the variability values at the
 250 edge of the patches are slightly lower than the 6dB threshold⁵³, probably due to the fact that the
 251 patches are not completely intercepted by the radar footprint and/or that they consist of wet sediments
 252 or small volumes of water (Supplementary Fig.3).



253
 254 (a)



(b)

Fig. 4 Spatial distribution of the normalized basal reflectivity (a) and normalized basal acuity (b) computed from the radar data collected at 4 MHz. White lines highlight the same red lines (observations) shown in Fig. 1b and used for the analysis of Fig. 3.

As a final step, we extended the approach followed by Orosei et al.⁷ to compute the basal water distribution map in terms of permittivity (Fig.5), in the area where a significant number of samples were present (Supplementary Fig. 6) and where the radar profiles were crossing each other (Methods). The map shows that the areas with high values of basal permittivity (15-40) correspond to the smooth areas (high acuity values) shown in Fig.4b, whereas the surroundings exhibit much lower values (about 6-8). On Earth, a permittivity value of 15 can be considered to be a threshold for the presence of liquid water in the basal material⁷; values below such threshold indicate that the material is dry or frozen. It is interesting to note that the central pond (permittivity ~40), which corresponds to the original main body of liquid water detected in Orosei et al.⁷, is separated from the other pools by strips of dry basal material. It is also the widest body of water and probably has the largest volume of liquid water of the entire hydraulic network.

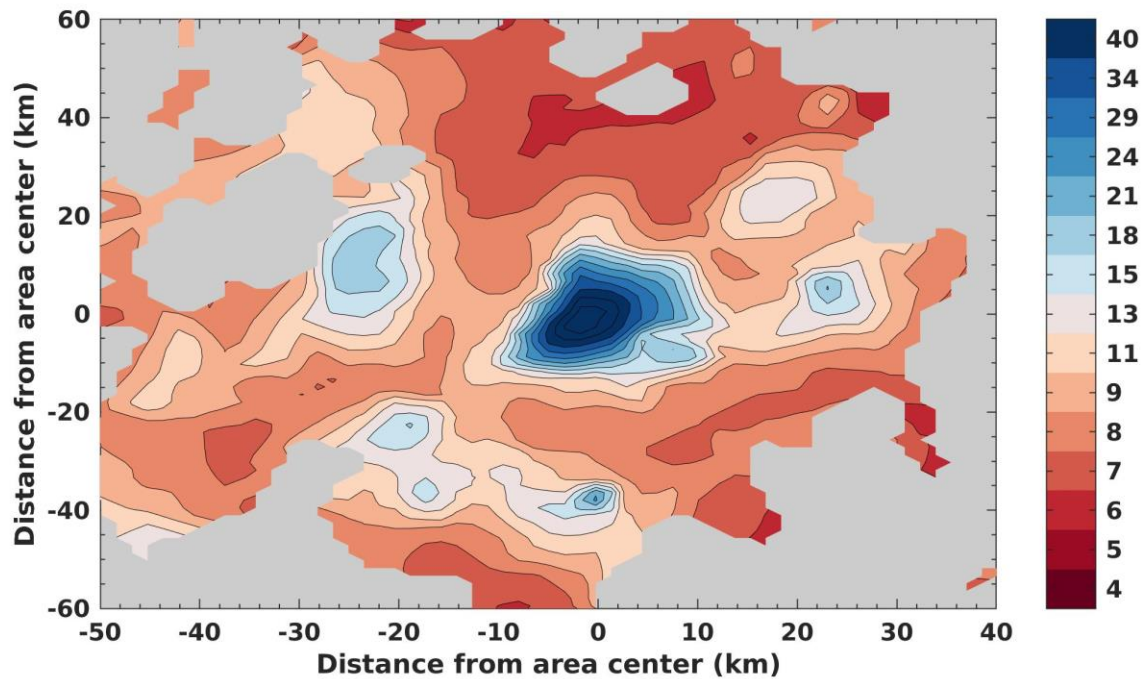


Fig. 5 Relative dielectric permittivity map computed by inverting the radar data. The gray patches correspond to areas where the number of samples is lower than 100, which is the minimum threshold to apply the probabilistic approach. This procedure has reduced the dimension of the study area to 90x120 km².

Mars subglacial lakes and the possible role of brines

Terrestrial subglacial lakes are known to have a variety of origins. Some are the remnants of isolated subaerial water bodies subsequently covered by ice sheets, as shown in the Canadian Arctic^{58,55} and in Antarctica^{59,60}, while others are hydrologically linked in a system of aquifers recharged by surface melting⁴⁷ or by ocean waters⁶¹. Investigations of the subglacial lakes of Antarctica⁶²⁻⁶⁴ highlight the critical contribution of the regional geological history to the formation and persistence of standing bodies of liquid water. Endogenic processes concurred to both the formation of topographic lows into which liquid water could flow and the existence of high geothermal gradients^{65-68,54}, as attested by the presence of volcanoes active in the Holocene (no earlier than ~ 12,000 years ago). Complex thaw-freeze cycles at the boundaries of the lakes, related to ice accumulation rates, and ice flow dynamics play a major role in the history of lake recharge and water residence times⁶⁹.

The technical and spatial resolution limitations of the MARSIS dataset do not allow a direct comparison of these Earth analogs with the Martian case. Furthermore, the unique combination of physical, geological, climatic and topographic conditions that could favor the formation of liquid water and its long term survival in a subglacial lake at the base of the SPLDs is, at best, a matter of speculation at this point in time. It is, however, possible to interpret relevant observations in the context of known experimental data and terrestrial analog studies to propose plausible processes for

296 the formation and persistence of subglacial liquid water on Mars. Combining evidence from radar
297 datasets and thermal models, subglacial hypersaline aqueous solutions were found to persist on Earth
298 at temperatures much lower than the freezing point of water⁷⁰. Thus, brines have been proposed as
299 the most plausible form of liquid water on the Martian surface and subsurface under present-day
300 physical conditions⁷¹, and have indeed been observed to flow on the Martian surface⁷².

301 The process of absorption of atmospheric water by perchlorates and the subsequent formation
302 of hypersaline solutions (i.e., deliquescence) was directly observed at the Phoenix Landing Site⁷³.
303 Considering that Ca-, Mg-, Na- and K- perchlorates, chlorates and hydrated chlorides⁷⁴⁻⁷⁷ are globally
304 ubiquitous in the Martian regolith, we posit that deliquescence and the formation of brines plausibly
305 occurs at the south polar latitudes as well. Experimental work has shown that soluble salts with low
306 eutectic temperatures deliquesce at low relative humidity values over a wide range of temperatures,
307 overlapping with those expected on Mars⁷⁸⁻⁸⁰, suggesting that brines may readily form in sub-polar
308 regions when the temperatures are in the higher range (e.g., at noon). Re-crystallization of brines
309 (efflorescence) when temperatures drop, however, is often kinetically inhibited⁸¹ because high
310 activation energies are required for the transition from liquid to solid (ordered) states. Freezing
311 experiments conducted under conditions similar to those on Mars have shown that perchlorate and
312 chloride brines may exist for long times after their formation without efflorescing^{82,83}. It is therefore
313 plausible that once formed, brines may exist on Mars in a metastable state for geologically significant
314 periods of time⁸⁴.

315 Orosei et al.⁷ suggested that the subglacial water discovered at Ultima Scopuli could be
316 hypersaline solutions. Subsequently, Sori and Bramson³⁴ computed the geothermal flux at the base
317 of the SPLDs that would melt ice when Na-, Mg- and Ca- perchlorates are present in the icy mixture.
318 They used Pestova et al.'s⁸⁵ eutectics for Mg- and Ca-perchlorate aqueous solutions, and Chevrier et
319 al.'s⁸⁶ eutectics for Na- perchlorate solutions, determining that an anomalously high geothermal flux
320 of 72 mW/m² is required for the icy mixture to achieve the temperature of the lowest eutectic (Ca-
321 perchlorate, 199 K). Recent experiments have shown, however, that Mg- and Ca-perchlorate-H₂O
322 solutions remain liquid in a super-cooled state at temperatures as low as 150 K⁸⁷. Mean temperatures
323 at the Ultima Scopuli location have been estimated to be approximately 160 K at the surface⁷,
324 increasing with depth by a few to a few tens of K per km, depending on the unknown geothermal flux
325 and thermal properties of the SPLDs. These temperatures are very close to the lower boundary of
326 super-cooled solutions, where kinetic processes are particularly important. We argue therefore, that
327 thermophysical modeling based on equilibrium conditions may not be wholly realistic in this context
328 and propose instead that metastable conditions are likely to produce a geologically significant effect,
329 both in terms of the formation of brines and in terms of their longevity on Mars.

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Our new and expanded methodological approach to the analysis of the earlier⁷ and new MARSIS data confirms the presence of a water lake at the base of the SPLDs in Ultima Scopuli, and further suggests that the bottom of the SPLDs is characterized by discrete areas of wetness around the main water body, possibly indicating that patches of ponded liquid water are not uncommon. Unfortunately, however, it will be difficult to find such bodies in other areas due to the unique surface characteristics of the investigated area (flat topography and smooth surface) and the limitations of the space-borne radar method. In any case, we are unable to conclusively determine whether the discovered Ultima Scopuli water bodies are hydrologically linked, but we believe that the new evidence presented here will substantially contribute to our understanding of the Martian hydrologic cycle.

Orosei et al.⁷ suggested that water at the base of the SPLDs was prevented from freezing owing to a high concentration of dissolved salts. In this paper we have presented a qualitative discussion on the conditions of brine stability which supports that interpretation. In the absence of heat flow data or geological evidence pointing to geothermal anomalies, models advocating recent magmatic activity to explain melting at the base of the SPLDs rely on largely speculative assumptions that disregard other key evidence acquired from planetary observations to date. We do not exclude the possibility that future missions might detect anomalous geothermal gradients in this region of Mars. We argue, however, that known physical and chemical properties of hypersaline aqueous solutions already provide a viable interpretive framework based on current observations and measurements of properties of the Martian surface and subsurface.

The possibility of extended hypersaline water bodies on Mars is particularly exciting because of the potential for the existence of microbial life, such as extremophiles, anaerobes⁸⁸ or even aerobes (considering that the solubility of O₂ in brines is up to 6 times the minimum level required for microbial respiration⁸⁹). The water bodies at the base of the SPLDs therefore represent areas of potential astrobiological interest and planetary protection concern, and future missions to Mars should target this region to acquire experimental data in relation to the basal hydrologic system, its chemistry, and traces of astrobiological activity.

Data and materials availability: The code that produces the figures and numerical results stated in the text is available from the corresponding author on reasonable request.

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- 621

622 **Methods**

623

624 **MARSIS data.** MARSIS radar is a nadir-looking pulse limited radar sounder that can operate in two
625 main observational modalities: Sub-Surface (SS) Mode and Active Ionosphere Sounding (AIS)
626 Mode. In SS mode, MARSIS transmits a 250 μs chirp with a 1MHz bandwidth. According to the
627 predicted Solar Zenith Angle (SZA), the chirp central frequency is selected among 4 different values
628 (1.8, 3, 4 and 5 MHz) to work well above the cut-off plasma frequency of the Martian ionosphere⁹⁰.
629 After range compression and Hanning windowing, the achievable range resolution in pure ice is about
630 55 m (assuming a velocity of 170 m/ μs). In this work, we only analyzed unprocessed data to avoid
631 the uncertainty due to the incoherent integration performed on-board in normal mode⁷. Two
632 alternative data acquisition methods were used⁹¹: i) the Flash Memory (FM) technique, which collects
633 discontinuous intervals of unprocessed/raw data along orbits; and ii) the Superframe acquisition
634 mode, which continuously collects data but along shorter orbits (Fig.1).
635 MARSIS data were collected in different years (2010 – 2019) and during different Martian seasons,
636 therefore each orbit refers to particular conditions of the Martian ionosphere. Because the ionosphere
637 can cause dispersion on the transmitted signal, reducing the echo intensity and producing a
638 broadening of the received signal, we normalized all quantities (i.e., surface and basal intensity and
639 acuity) to the median of the relevant surface quantity along each orbit. In particular, the use of the
640 median minimizes the effects caused by local surface echo power fluctuations, which are sometimes
641 observed in the data, without altering the along track variation of the basal reflectivity and acuity.
642 In this work we present and discuss only the data collected at 4MHz, as it is the largest and most
643 robust dataset. The data collected at the other frequencies are sparser (especially the 3MHz that is
644 also more affected by the ionosphere) and thus less statistically significant (Supplementary Fig.1).
645 Despite this fact, the analysis of such data supports the results obtained at 4MHz.

646

647 **Spatial smoothing and acuity.** We processed MARSIS data according to the method developed by
648 Oswald and Gogineni⁴⁸, which applies an along-track average to the radar traces (spatial smoothing)
649 in order to reduce the power variance due to variable roughness^{92,43}. In our analysis, the along-track
650 waveform averaging window W is set equal to the diameter of the pulse-limited footprint area:

$$651 \quad W = 2\sqrt{c\frac{p}{2}\left(H + \frac{z}{n}\right)} \cong 2\sqrt{c\frac{p}{2}H}, \quad (1)$$

652 where $p = 1\mu\text{s}$ is the transmitted pulse length, H is the spacecraft altitude (this quantity can vary
653 between 250 and 900 km), c is velocity of light in a vacuum, z is the depth of the reflector and $n \cong$

654 1.71 is the water ice refractive index. For example, considering a spacecraft height $H = 400\text{km}$ the
 655 resulting window is $W \cong 15\text{km}$.

656 In addition, we computed the acuity A_c , which is an indication of interface roughness, from the depth
 657 aggregated echo power⁵² as follows:

$$658 \quad A_c = \frac{\max\{x_r^2(t)\}}{\sum_{t=\tau-T/2}^{\tau+T/2} x_r^2(t)}, \quad (2)$$

659 where $x_r(t)$ is the received pulse generated by a reflector located at a time delay τ (e.g., surface or
 660 bedrock), $T = \sqrt{\frac{H}{2\nu c}}$ (ν is the operating frequency).

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663 **Basal topography and hydraulic potential.** We computed the basal topography (B) and the
 664 hydraulic potential (ϕ_H) along the observations reported in Fig.3 according to the following
 665 equations⁹³:

$$666 \quad B = S - h \quad (3)$$

667 and

$$668 \quad \phi_H = \rho_w g_M (S - h(1 - \rho_{ice}/\rho_w)) \quad (4)$$

669 Where S is the surface topography (based on MOLA data), h is the SPLDs thickness computed
 670 assuming a permittivity $\epsilon_{ice} = 3.4$, $\rho_w = 1980 \text{ kg/m}^3$ is the density of the perchlorate solution³³,
 671 $\rho_{ice} = 1100 \text{ kg/m}^3$ the average density of the SPLDs⁹⁴ and $g_M = 3.72 \text{ m/s}^2$ is the Martian gravity
 672 (Supplementary Fig.2). The uncertainties Δu associated with these parameters (where $u = B$ or $u =$
 673 ϕ_H , depending on the used equation) have been computed applying the statistical propagation
 674 formula⁹⁵, under the assumption that all uncertainties are independent and uncorrelated:

$$675 \quad \Delta u = \sqrt{\sum_i \left(\frac{\partial u}{\partial x_i} \Delta x_i \right)^2} \quad (5)$$

676 where x_i are the variables (e.g. $S, h, \dots$) in equations 3 and 4 and Δx_i the associated uncertainties. In
 677 Eq. (5) $\Delta h = 61\text{m}$, $\Delta S = 61\text{m}$ and $\Delta \rho_{ice} = 115 \text{ kg/m}^3$. Note that we have neglected the
 678 uncertainties related to the density of perchlorate brines and Martian gravity.

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681 **Bed-echo intensity variability.** We used the intensity variability parameter σ_I to localize the
 682 transition between dry (or frozen) and wet bed conditions⁵³. The parameter σ_I is given by:

683

$$684 \quad \sigma_I = \Delta R \sqrt{f^2(1-f) + (1-f)^2 f} \quad (6)$$

685

686 where

687

$$688 \quad \Delta R = 20 \log_{10} \left(\left| \frac{\sqrt{\varepsilon_b} - \sqrt{\varepsilon_{ice}}}{\sqrt{\varepsilon_b} + \sqrt{\varepsilon_{ice}}} \right| \left| \frac{\sqrt{\varepsilon_{dry}} + \sqrt{\varepsilon_{ice}}}{\sqrt{\varepsilon_{dry}} - \sqrt{\varepsilon_{ice}}} \right| \right) \quad (7)$$

689

690 With ε_b the dielectric permittivity of the basal material, ε_{ice} the permittivity of the SPLDs and ε_{dry}
 691 the permittivity of the dry rock. In addition, f is the fraction of wet area (wet–dry mixing ratio in
 692 Jordan et al.⁵³) inside the radar footprint. Supplementary Fig.3 illustrates the intensity variability as
 693 a function of the basal permittivity for two values of the mixing ratio f .

694 We computed the intensity variability σ_I (expressed in dB) along each orbit at x_i position, as follows:

695

$$696 \quad \sigma_I(x_i) = \frac{10}{\ln(10)} \frac{\sqrt{\frac{1}{N} \sum_{x=x_i-W/2}^{x_i+W/2} [P_{ag}(x) - \langle P_{ag}(x_i) \rangle]^2}}{\langle P_{ag}(x_i) \rangle} \quad (8)$$

697 where $P_{ag}(x)$ is the aggregated power computed according to Jordan et al.⁵³, and $\langle P_{ag}(x_i) \rangle$ is the
 698 average echo power:

$$699 \quad \langle P_{ag}(x_i) \rangle = \frac{1}{N} \sum_{x=x_i-W/2}^{x_i+W/2} P_{ag}(x) \quad (9)$$

700

701 The observations collected around the bright area show specific values of the bed-echo intensity
 702 variability. In particular, the radar observations crossing approximately the center of the main body
 703 of liquid water (Fig.3 and Supplementary Fig.4 and Fig.5) exhibit an intensity variability exceeding
 704 the fairly conservative threshold of 6dB⁵³ and therefore clearly indicate a transition from dry to wet
 705 basal material. On the other hand, the observations passing on the edge of the main body or on the
 706 other patches, even if still showing an abrupt change in intensity variability, do not exceed 4-5dB.
 707 These results can be explained considering the intersection between the radar footprint and the bed
 708 conditions (dry/wet), which is accounted for by the parameter f (Supplementary Fig.3, Fig.4 and
 709 Fig.5).

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711 **Permittivity map.**

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713 The basal permittivity map was generated applying an inversion probabilistic approach⁹⁶ to the
 714 intensity values collected along the radar profiles shown in Fig. 1b. The procedure and the parameters
 715 used are reported in Lauro et al.⁸.

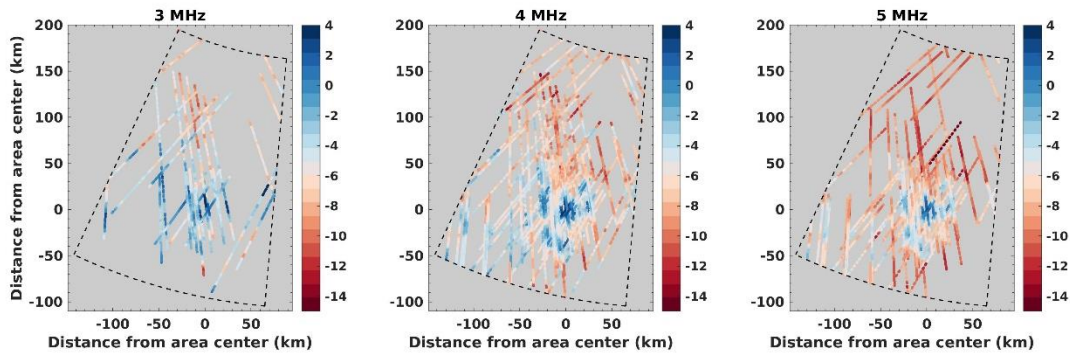
716 As a first step, to generate the map reported in Fig.5, we applied a mesh refinement technique to
717 obtain pixels containing about 100 samples. All pixels having fewer samples were discarded. For
718 each pixel, we computed a probability density function of the basal permittivity and we assigned the
719 median value of such distribution to the pixel coordinates in the scatter map (Supplementary Fig. 6).
720 Our analysis was focused on the area having the highest pixel density (white dashed box in
721 Supplementary Fig. 6) which was interpolated to generate a contour map (Fig. 5). Nevertheless, the
722 areas with lower pixel densities (outside the white dashed box) are very consistent (spatial continuity)
723 and characterized by low permittivity values (dry rocks) except for a small area in the North-East,
724 where the permittivity values are higher. This latter area was not included in the analysis given the
725 low MARSIS coverage and the lack of crossing orbits.

726 Note that, in the inversion procedure, both surface and basal roughness were not accounted for. In the
727 area, the surface is very smooth at the MARSIS scale⁹⁷ whereas the basal roughness is not well
728 constrained. Therefore, the basal permittivity (Fig.5) computed with the inversion could be, in
729 principle, underestimated⁹⁸. However, this is not the case for the main body of liquid water as the
730 subsurface and surface acuity values are similar (Fig.3b). The acuity values measured on the other
731 patches of water are only slightly lower, suggesting that, if present, the underestimation of the
732 permittivity should not be very large.

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737 **Supplementary information**

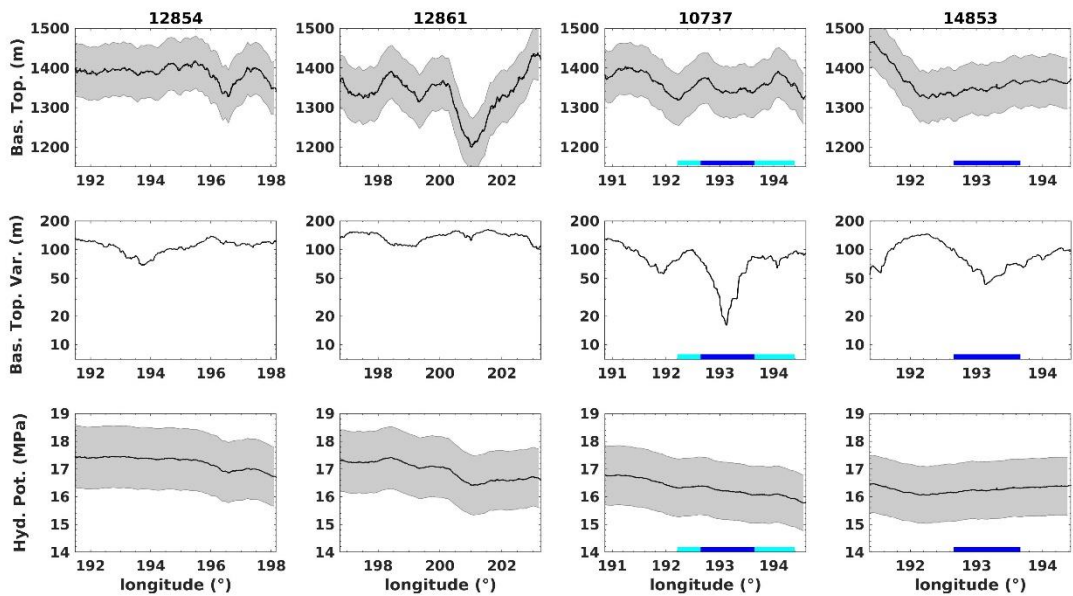
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740 Supplementary Fig.1 Normalized basal reflectivity maps of the observations collected in the
741 investigated area (185-205E and 79.5-84.1S) at 3, 4 and 5MHz.

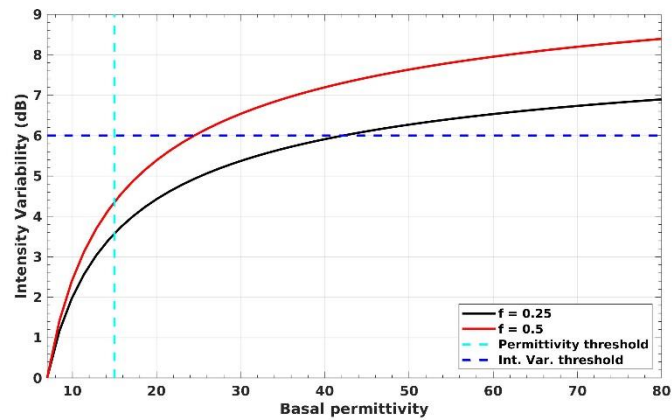
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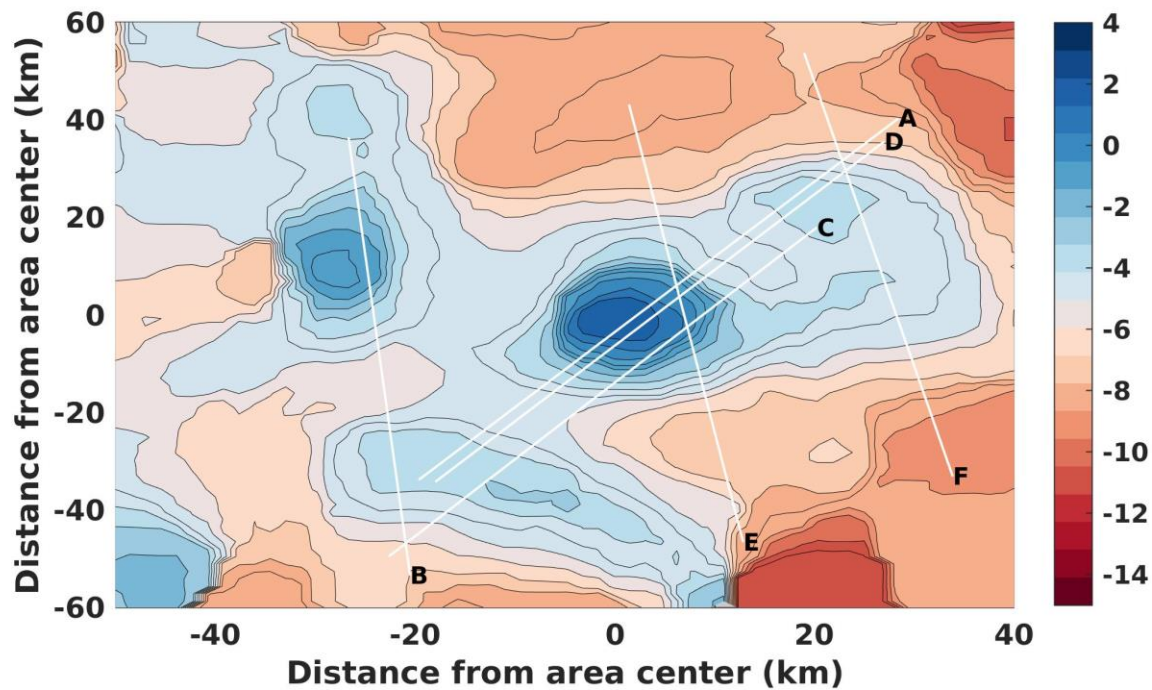
744 Supplementary Fig.2 Top row indicates the basal topography with the associated uncertainty (gray
745 band). The central row represents the basal topography variability, computed applying a moving
746 average window (Eq.1), which shows local minima in correspondence to the main body of water
747 (dark blue lines). Bottom row represents the hydraulic potential with relevant uncertainty (gray band).
748 The first two columns refer to the observations collected outside the bright area and the last two those
749 collected inside the bright area. Dark blue lines indicate the position of the main body of liquid water,
750 cyan lines the lateral water patches. In the wet areas the along-track variations of basal topography
751 and hydraulic potential are of the same order of magnitude as the uncertainties, indicating that
752 MARSIS does not have the sensitivity to measure such variations.

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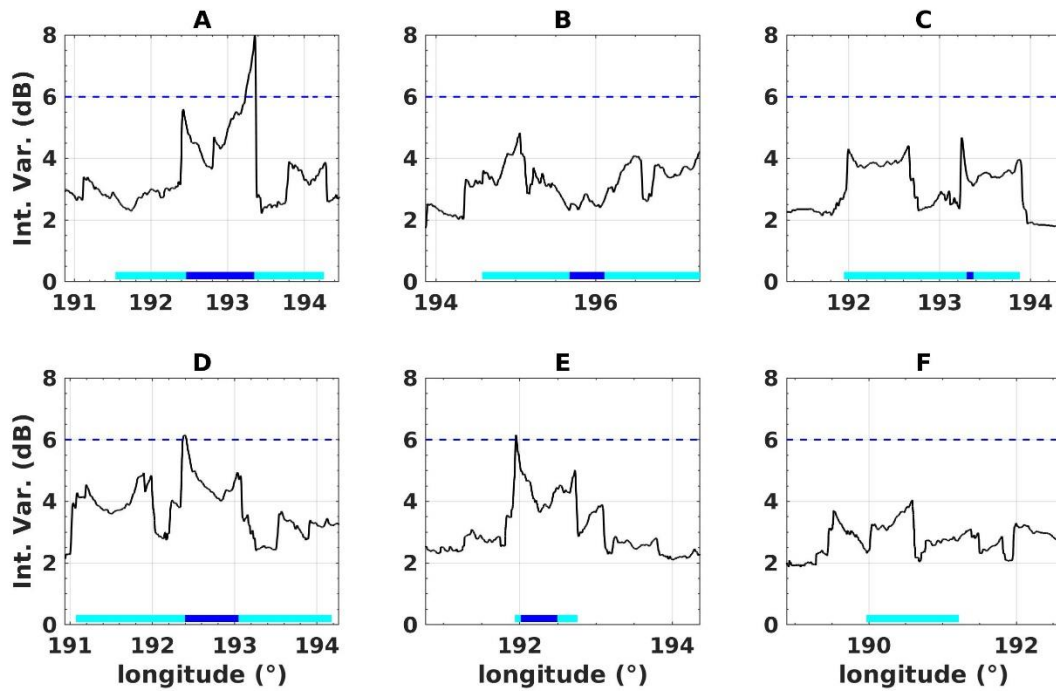
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Supplementary Fig. 3 Intensity variability computed using equations 3 and 4, assuming $\varepsilon_{dry} = 7$ and considering two different wet-dry mixing ratios (black and red lines). The cyan dashed line represents the permittivity threshold $\varepsilon_b = 15$ which, on Earth, is usually associated with wet materials⁷ and the dashed blue line is the intensity variability threshold for dry to wet basal transition⁵³.



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Supplementary Fig.4 Enlargement of the normalized basal intensity map shown in Fig.4a. White lines highlight six observations crossing the main body of water and the lateral patches.



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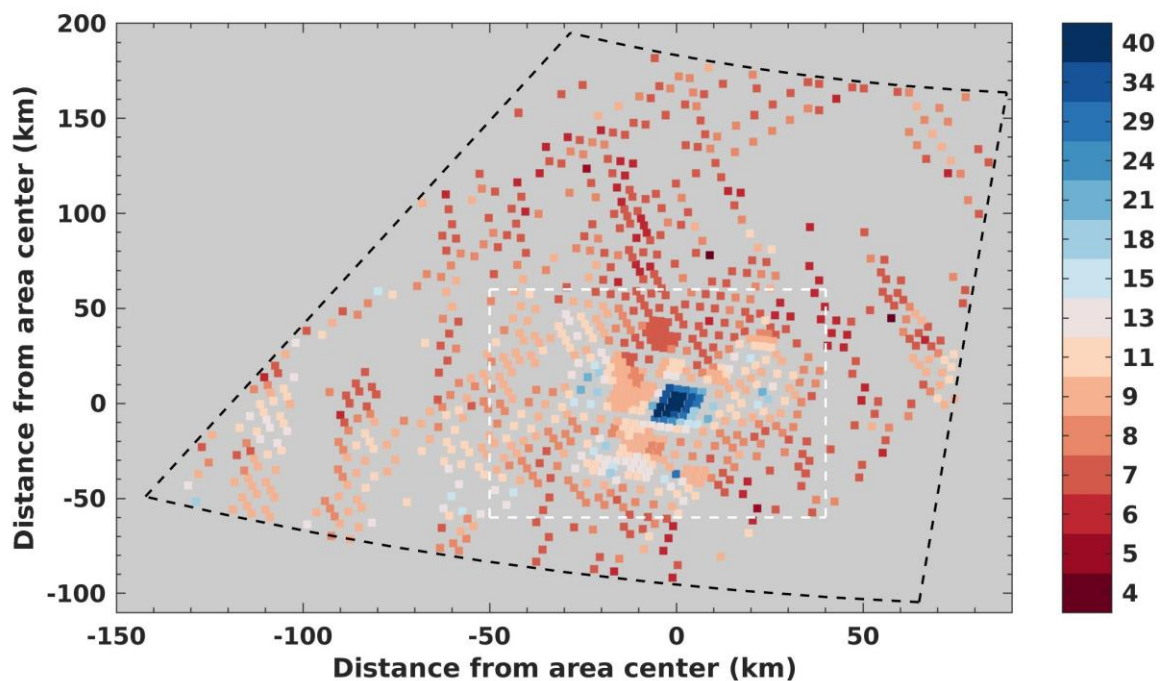
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Supplementary Fig.5 Intensity variability values computed using equation 3 for the six observations illustrated in Supplementary Fig. 4. The blue dashed lines mark the intensity variability threshold for the dry-wet transition according to Jordan et al.⁵³. Dark blue lines indicate the position of the main body of liquid water, cyan lines the lateral water patches.



775

776 Supplementary Fig. 6 Scatter map of the basal permittivity. The white dashed box indicates the area
777 analyzed in Fig. 5. The size of the dots in the map is not representative of the pixel dimension.