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# Evidence of mud volcanism due to the rapid compaction of Martian tsunami deposits in southeastern Acidalia Planitia, Mars

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## **Abstract**

Thumbprint terrain was first recognized in Viking Orbiter data and described as sets of alternating continuous parallel ridges and depressions up to several tens of kilometres in length, with high and low albedo respectively. We performed a geomorphological analysis of these features using both Context Camera and High Resolution Imaging Science Experiment images, as well as topographic profiles based on Mars Orbiter Laser Altimeter data, with the aim to provide an origin for thumbprint terrain and constrain the geological evolution of southeastern Acidalia Planitia. The identification of runup lobate deposits, coupled with the putative presence of a Late Hesperian ocean in the northern lowlands, led to speculations that evidence of tsunamis may be present in the geologic record of the area. There are several hypotheses that have been proposed previously to explain the origin of thumbprint terrain and include ice-related, volcanic-related, liquefaction and mud-volcanism driven processes. However, a tsunami-related origin provides a strong geological framework for the energy required for the associated lobes to flow uphill and leaving peripheral termination ridges as a result of viscosity. Numerical simulations indicate that - prior to their emplacement - the lobes sustained high velocities, thereby lending further support to the tsunami hypothesis and their origin from the Lomonosov crater impact. Wave interference patterns, formed during the propagation of the tsunamis over and around prominent topography, likely explain the thumbprint terrain spatial arrangement. The thumbprint terrain sedimentary cones are, herein, considered mud volcanoes related to a tsunami that occurred in southeastern Acidalia Planitia.

## 1 Introduction

The presence of a Hesperian ocean within the northern plains is one of the most debated issues of the Martian geology (Parker et al., 1989, 1993; Head et al., 1998, 1999; Clifford and Parker, 2001; Carr and Head, 2003; Tanaka et al., 2003, 2005). Its presence would imply that northern lowlands gathered a large quantity of water and sediments. Outflow channels, carved by large-scale floods (Carr, 1979), are commonly thought to have served as the primary supply of water which may have filled the northern lowlands in the Late Hesperian (Parker et al., 1989, 1993; Baker et al., 1991; Clifford and Parker, 2001; Tanaka et al., 2005). The ocean-hypothesis is supported by several flat surfaces that can be observed spanning thousands of kilometres and marking distinct units in the peripheral northern lowlands. These limits have been interpreted as paleo-shorelines (Parker et al., 1989, 1993; Clifford and Parker, 2001); for example, the Deuteronilus contact is characterized by very slight topographic variations ( $-3792 \pm 236$  m), which are strikingly consistent with the paleo-shoreline hypothesis (Clifford and Parker, 2001; Carr and Head, 2003; Perron et al., 2007; Citron et al., 2018). On the other hand, some limits (i.e., Arabia contact) have topographic amplitudes of up to several kilometres that have initially been used against the ocean hypothesis (Head et al., 1998; Head et al., 1999; Carr and Head, 2003). However, recent studies proposed that these limits represent deformed paleo-shorelines as the result of deformation related to true polar wander occurring before and during the massive Tharsis volcanic rise (Citron et al., 2018; Zuber, 2018) or after the formation of Tharsis region (Perron et al., 2007). Several studies have also showed that there could be a large reservoir of water/mud in the deepest portions of the Utopia basin during the Hesperian (Ivanov et al., 2014; Ivanov et al., 2015). This may potentially represent the remnant of a larger standing body of water, further supporting the presence of an ocean within the northern plains (Parker et al., 1989, 1993; Head et al., 1998, 1999; Clifford and Parker, 2001; Carr and Head, 2003; Tanaka et al., 2003, 2005).

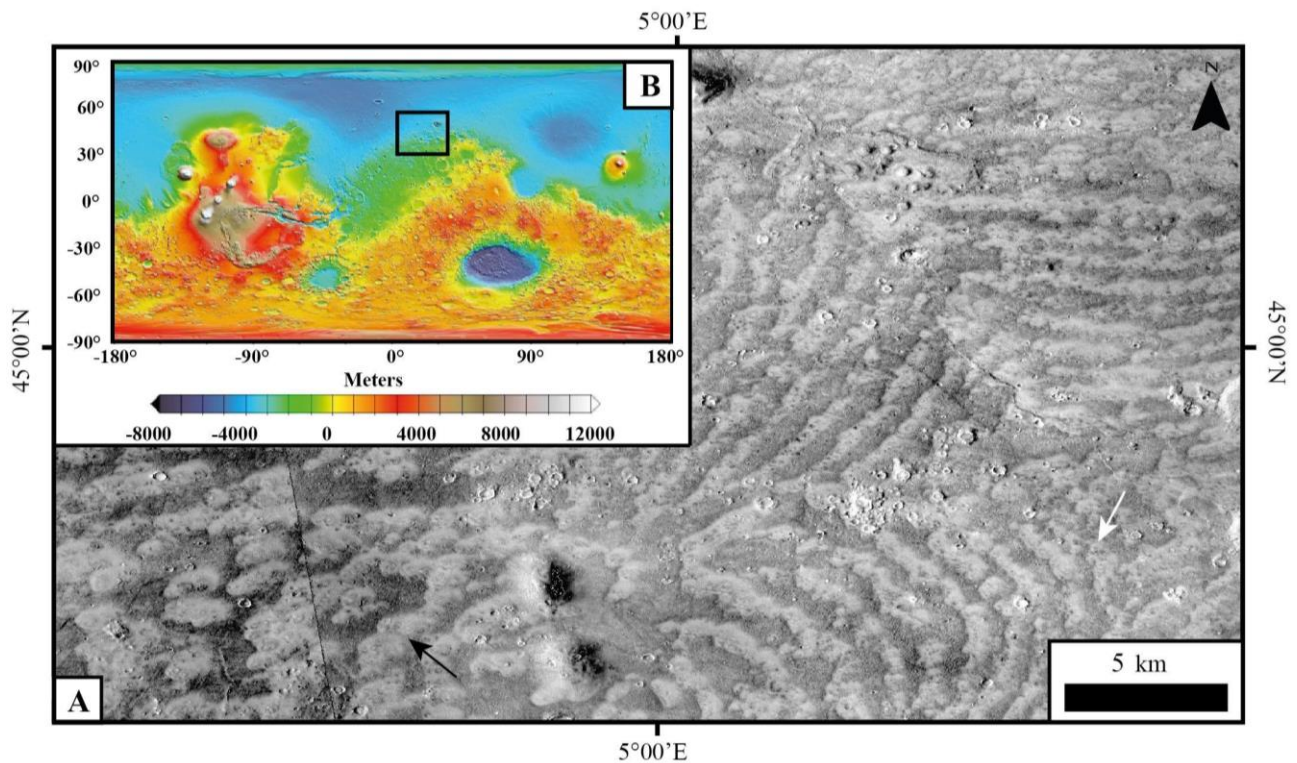


Figure 1. Thumbprint terrain in Acidalia Planitia. A) Thumbprint terrain at low resolution with a random arrangement (black arrow) on the left and an arcuate and parallel linear disposition (white arrow). B) Study area is marked by the black rectangle on the topographic map based on colorized Mars Orbiter Laser Altimeter data. Courtesy of NASA/JPL/Univ. of Arizona.

Thumbprint terrain (represented hereafter as TT) was previously recognized and described as continuous parallel and curvilinear ridges at regional scale (Fig. 1A – white arrow) on the basis of Viking Orbiter data (Lockwood et al., 1992). However, the wealth and increasing resolution of remotely sensed imagery showed it is comprised of both randomly (Fig. 1A – black arrow) and highly organized (Fig. 1A – white arrow) spatial patterns of individual pitted cones/small mounds that lie above lobate deposits. Thumbprint terrain overlies millions of square kilometres primarily in the northern plains between 30°N and 50° (e.g., Acidalia Planitia, Utopia Planitia, etc...), although they also occur in a large area near the Martian equator (i.e., Isidis Planitia). Several hypotheses have been proposed for the origin of thumbprint terrain; with the majority of them involving the presence of ice/water. The individual cones were first interpreted as possible pseudo-craters formed by explosions associated with lava emplacement over wet ground (Frey and Jarosewich, 1982; Carr, 1986), cinder cones (Scott et al., 1995), pingos, ice-cored ridges (Lucchitta, 1981; Rossbacher and Judson, 1981), moraines (Lucchitta, 1981; Scott and Underwood, 1991; Kargel and Strom, 1992; Lockwood et al., 1992), or mounds formed by the disintegration of stagnant ice covers (Grizzaffi and Schultz, 1989). According to the most recent hypotheses, they are interpreted as mud

volcanism-driven deposits (Tanaka et al., 2003; Salvatore and Christensen, 2014), liquefaction deposits (Skinner et al., 2008; Skinner and Fergason, 2010) or related to impact-generated tsunami lobate deposits (Rodriguez et al, 2016; Costard et al, 2017; Costard et al., 2019).

On Earth, the most common triggers of tsunamis are earthquakes, subaqueous landslides, and volcanic activity. Only on rare occasions meteorite crashes give rise to tsunamis, thus terrestrial impact-induced tsunami deposits are sparse (Paris et al., 2009; Bryant, 2001). Conversely, on Mars, impact-generated tsunamis seem to be a plausible trigger mechanism. The study area (SE Acidalia Planitia) is uniquely positioned in that numerical modelling and geologic investigation tie an asteroid impact (e.g., Lomonosov crater) to the generation of a tsunami wave (Iijima et al., 2014; Rodriguez et al, 2016; Costard et al, 2017; Costard et al., 2019) that extended to the areas covered by thumbprint terrain. These numerical predictions, combined with geologic observations, demonstrate the importance of the study area and provides a convincing scenario for thumbprint terrain origin.

Here, we focused on thumbprint terrain (or TT), i.e. alignments of cones or mounds, in the southeastern Acidalia Planitia near the dichotomy (43°-53° N 0°-22° E; Fig. 1B), in an effort to: (i) characterize their geographical distribution; (ii) describe their morphology and relationship with former/underlying topography around the dichotomy and (iii) discuss their origin considering evidences and regional geological context. We will refer to alignments of cones/mounds simply as “thumbprint terrain” or “TT”; while we will refer to both thumbprint terrain and underlying associated lobate deposits as “lobate TT unit”. Although lobate deposits were not the focus of this study, it is useful to have a terminology that indicates both thumbprint terrain and underlying lobes when discussing the overall evolution of the area since target morphologies (TT) are closely related to lobate deposits in SE Acidalia Planitia.

## **2 Stratigraphy**

The Vastitas Borealis Formation is the most widespread formation in the northern lowlands (Greeley and Guest, 1987; Tanaka and Scott, 1987). Many different hypotheses have been proposed to explain its origin, supporting either a sedimentary

processes related to outflow channels (Kreslavsky and Head, 2002) or a volcanic process (Catling et al., 2012). Kreslavsky and Head (2002) asserted that a sedimentary section of the Vastitas Borealis Formation formed as a residue when water from the outflow channels settled, quickly froze, and then sublimated. However, recent studies suggested that portions of Vastitas Borealis Formation were emplaced and/or modified while still saturated with liquid water (McGill and Hills, 1992; Tuckwell et al., 2003; Buczkowski and Cooke, 2004; Cooke et al., 2011; McGowan, 2011; Buczkowski et al., 2012). Regional geologic mapping (Tanaka et al., 2005; Fig. 2) separated the Vastitas Borealis Formation into two distinct units: the interior (ABvi) and the marginal unit (ABvm). The ABvi unit is the more extensive of the two units and hosts most of the diagnostic Vastitas Borealis Formation morphological features (Salvatore and Christensen, 2014). Data from Mars Orbiter Laser Altimeter (MOLA) derived Digital Elevation Model (DEM) and several 100-m/pixel-resolution Thermal Emission Imaging System images (THEMIS) reveals that the ABvi unit is rougher and has a higher thermal inertia than the ABvm unit (Tanaka et al., 2005, and references therein). The ABvi unit also consists of relatively bumpy, plains-forming material (Tanaka et al., 2005) that covers most of the northern plains including Vastitas Borealis and Utopia, Acidalia, and northern Arcadia Planitiae. The outer parts of the ABvi unit include the lobate TT unit (Fig. 2), as well as random clusters of hills mostly <1 km across (Frey and Jarosewich, 1982; Grizzaffi and Schultz, 1989; Scott et al., 1995). Approaching the edge of the unit, cones/mounds tend to decrease in quantity, occurring in random and small groups until their complete disappearance (Tanaka et al., 2005; Salvatore and Christensen, 2014). Conversely, the ABvm unit outcrops surround the ABvi in Utopia Planitia, along Arabia Terra, in southern Acidalia Planitia, north of Alba Patera, and in western Arcadia Planitia. At lower latitudes (< 25° N), it appears smoother, exhibits a higher albedo and lower thermal inertia than both the ABvi unit and surrounding materials in THEMIS daytime infrared images. This means that the ABvm unit is warmer, which may indicate a relatively fine-grained material compared to adjacent materials (Tanaka et al., 2005). Parts of the ABvm are buried by Amazonis and Elysium provinces materials. The ABvm unit also includes systems of fretted valleys that are a few kilometres wide and tens of kilometres long (Squyres, 1978; Carr, 1995; Tanaka et al., 2005). These features have no clear terrestrial analogues and they have previously been compared to glacial moraines and kame complexes (Lucchitta, 1981), glacial tunnel valley and esker features (Kargel et al., 1995), or soft-sediment deformation structures (Tanaka et al.,

2003). The Vastitas Borealis marginal and interior units generally have a poorly defined contact and post-emplacment material evolution. In addition, the southern limit of the collective outer margin of both Vastitas Borealis units is fairly constant in elevation ( $\sim 3900\text{m} \pm 70\text{m}$ ) and close to the mean elevation of the Deuteronilus contact (see section 1), hence it may indicate the presence of an ancient standing body of water (Parker et al., 1989, 1993; Head et al., 1999; Clifford and Parker, 2001; Carr and Head, 2003). In our study area, the Vastitas Borealis Formation approaches the Noachis Terra unit (Nn) (Fig. 2) and to a lesser extent the Deuteronilus Mensae 1 unit (HBd1; Mangold et al., 2002) (Fig. 2). The Noachis Terra unit is Middle to Late Noachian in age and represents mostly heavily cratered terrain (Tanaka et al., 2005). Most of the unit displays layering (Malin and Edgett, 2001), in MOC narrow-angle data. Elevation ranges between  $-2,000$  and  $-5,000$  m within the northern plains across Orcus Patera and Acidalia Mensa (Tanaka et al., 2005).

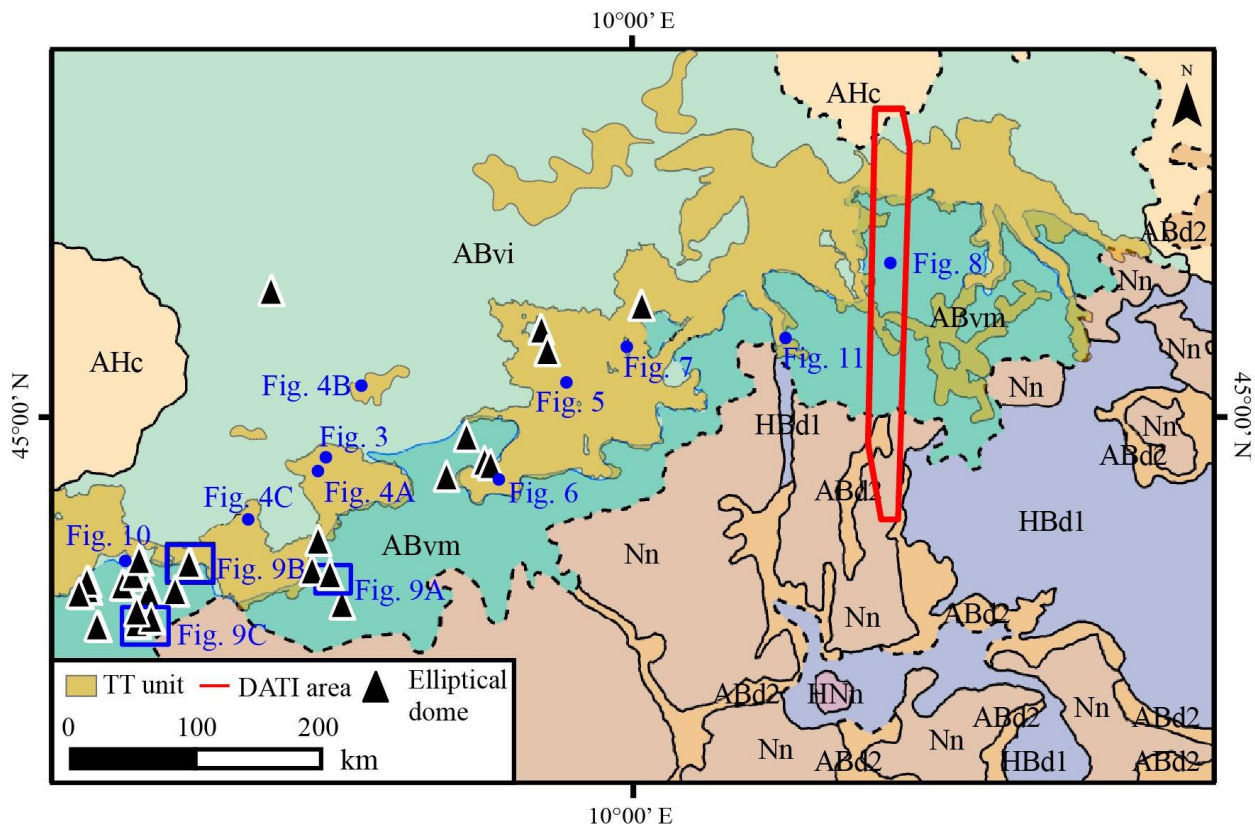


Figure 2. Background geological map is 'US Geological Survey Sci. Inv. Map 2888' by Tanaka et al., 2005. Lobate TT unit extension is marked by the orange polygons and covers an area bigger than  $10^5$  km<sup>2</sup>. Red frame indicates the area of quantitative thermal inertia analysis (See section 3). Elliptical domes related to the thumbprint terrain (see Fig. 9-10) are localized outside or along the boundary of the thumbprint area (black triangles are not to scale). The lobate TT unit was mapped crossing both the Vastitas Borealis interior unit (ABvi) and Vastitas Borealis marginal unit (ABvm). Other geologic units: Nn - Noachis Terra Unit; HBd1 - Deuteronilus Mensae unit 1; ABd2 - Deuteronilus Mensae 2 units; HNn -



*Nepenthes Mensae* unit. See Tanaka et al. 2005, for a more complete description. Courtesy of NASA/USGS.

### 3 Data and Methods

Context Camera (CTX; 6m/pixel) (Malin et al., 2007) and High Resolution Imaging Science Experiment (HiRISE; 0.25-0.32m/pixel) (McEwen et al., 2007) images were used to investigate thumbprint terrain. CTX images provided a full coverage of the study area to be compared with Mars Orbiter Laser Altimeter (MOLA; Smith et al., 2001) digital elevation model (DEM) which provided the topographic base map with a spatial resolution of 463 m. Detailed topographic profiles were performed from MOLA laser shots (vertical resolution: 50 cm; size of the laser shot on the surface: 128 m) to investigate and to provide a topographic context for TT morphologies and associated lobate deposits (e.g. Fig.3 and following) thanks to MOLA Precision Experiment Data record (PEDR) facility available at the Photothèque Planétaire d'Orsay, France (<http://fototek.geol.upsud.fr/-Mars-Orbiter-Laser-Altimeter-.html>). Mars Odyssey (ODY) Thermal Emission Imaging System (THEMIS) daytime and night-time infrared (IR) images (100m/pixel; Christensen et al., 2004) were also used to investigate the thermo-physical properties, including thermal inertia that quantifies the physical properties and average particle sizes of surface textures and morphologies (Ferguson et al., 2006). Relief characteristics (slopes and aspects) for the relief correction of albedo and temperature difference (input parameters in Eq. 1) were calculated based on the High Resolution Stereoscopic Camera (HRSC) DEM-s (spatial resolution: 100 m; Neukum and Jaumann, 2004; Jaumann et al., 2007) in \*da4.img format (aeroid directly comparable with MOLA grid) acquired from Mars Orbital Data Explorer (<http://ode.rsl.wustl.edu/mars/>).

#### 3.1 Thermal inertia estimation

We performed a quantitative detailed analysis of thermal inertia on a selected portion of the studied area (Fig. 2). As direct measurement of thermal inertia was not possible to estimate; Differential Apparent Thermal Inertia (DATI) was computed as follows:

$$DATI = \frac{1-A}{\Delta T} \quad [\text{Eq. 1}]$$

- 1 where A is the albedo and  $\Delta T$  is the temperature difference. DATI technique (Sabot et
- 2 al., 2006) is proportional to P ('direct' thermal inertia) and is calculated based on short

3 time (t) intervals (at least one hour time difference) with a high  $|\Delta T/\Delta t|$  gradient (in the  
4 morning or in the afternoon), preferably during the same period of the year (similar solar  
5 longitude). The selected part of SE Acidalia Planitia was chosen on the base of: (i) data  
6 availability for DATI calculation (i.e., high quality images with appropriate time interval,  
7 in the same period of the year), and (ii) the presence of the key landforms (thumbprint  
8 terrain). THEMIS IR images were processed online using the Themis Processing Web  
9 Interface (THMPROC; <http://thmproc.mars.asu.edu>). To calculate the Differential  
10 Apparent Thermal Inertia (Eq. 1), high quality THEMIS images were chosen: the  
11 minimum and maximum “summing” parameters were set to 1 (full-resolution images),  
12 while the minimum and maximum “image rating values” were set to 4 and 7,  
13 respectively. These parameters depend on a subjective assessment of the image  
14 quality ranging from 1 (unusable) to 7 (very good); this assessment includes  
15 consideration of exposure, missing lines, instrument noise, and atmospheric features.  
16 Relief correction for A and  $\Delta T$  was also performed since this kind of calibration is not  
17 included in thermal inertia modelling. Temperature difference ( $\Delta T$ ) was additionally  
18 calibrated against total incoming energy. Atmospheric correction was also included. In  
19 order to avoid large errors by calculating DATI and albedo, the cells with  $i > 79^\circ$  were  
20 excluded from the calculations.

21 The uncertainty in DATI calculation arises from errors due to dust opacity, albedo and  
22 slope inclination. The errors in daytime THEMIS temperatures may be  $\pm 3$  K (Ferguson  
23 et al., 2006). Assuming the temperature amplitude is 20 K and albedo is 0.2, a  $\pm 3$  K  
24 error implies 17% relative error on thermal inertia due to the error of each of two  
25 measured temperatures. Dust opacity is  $1.6 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  making up 0.8% of the  
26 average DATI, ( $200 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ ), and standard deviation (SD) due to seasonal  
27 variation of dust opacity in the high-dust season, which is 0.1. We estimate that a dust  
28 opacity error of 0.1 generates a relative error of 5.6% on apparent thermal inertia by  
29 comparing average DATI values corrected for dust opacities of 0.22 (average), 0.32  
30 (average +1 SD) and 0.12 (average -1 SD). Considering the two errors of 0.8% and  
31 5.6%, the total uncertainty related to dust opacity is 5.7% when applying the rule of  
32 error propagation for error addition. The uncertainty of albedo calculation is 8% which  
33 generates a 1.5% error on DATI values. The error in computation of slope inclination on  
34 HRSC DTM is  $\sim 4^\circ$  (Heipke et al., 2007), which can potentially add up to 35% of error on  
35 DATI values where the incidence angle is very high ( $79^\circ$ ). This is calculated by

36 comparing DATIs for 79° to the average DATI for 75° and 83°, provided all other  
37 parameters are fixed at typical values. In the most common case where the incidence  
38 angle is in the range 0°– 50°, the DATI error is within 10%. Taking temperature, dust  
39 opacity, slope inclination and albedo into account, the total uncertainty on DATI is  
40 estimated to be within 27%. However, it can reach up to 43% when the incidence angle  
41 is 79°.

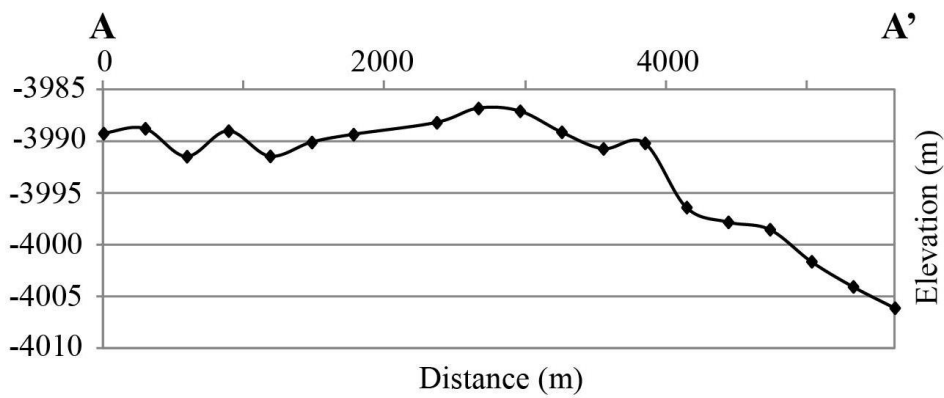
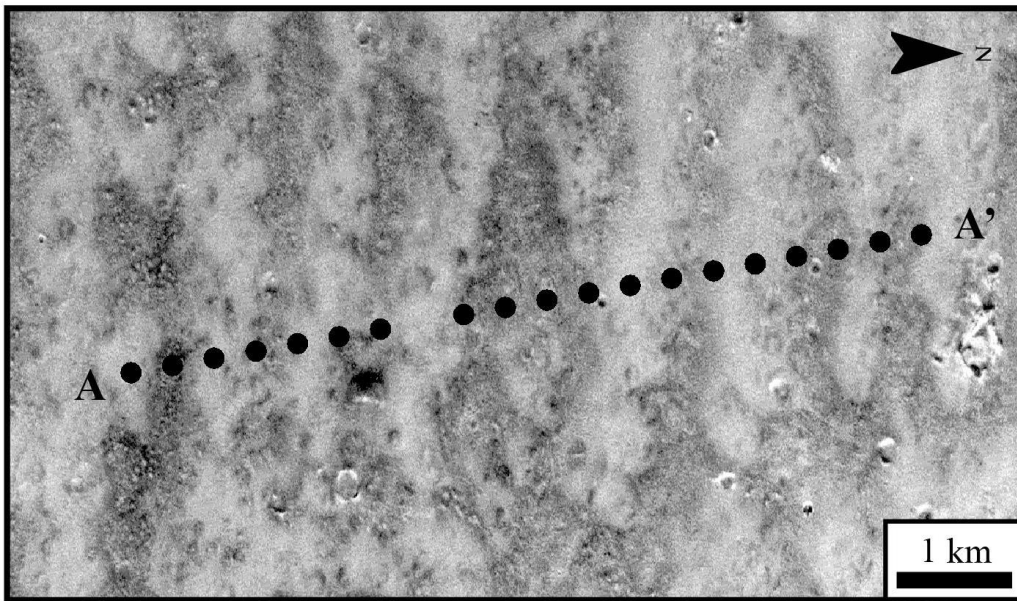
42

### 43 **3.2 Crater-size frequency distribution**

44 We performed a crater counting analysis using CTX imagery to provide an age  
45 estimation for the lobate TT unit deposits. All visible impact craters (>500 m in diameter)  
46 were measured except the aligned secondary clusters and rays within the CTX  
47 resolution limit using the ArcGIS add-in CraterTools (Kneissl et al., 2011; Bamberg et  
48 al., 2013). The crater-size frequency distribution (CSFD) was plotted and the crater  
49 retention ages were calculated with Craterstats by visually selecting the portion of the  
50 crater size-frequency distributions that is parallel to some isochrons between steps of  
51 the distribution (Neukum, 1983; Hartmann and Neukum, 2001; Platz et al., 2013).

## 52 **4 Results**

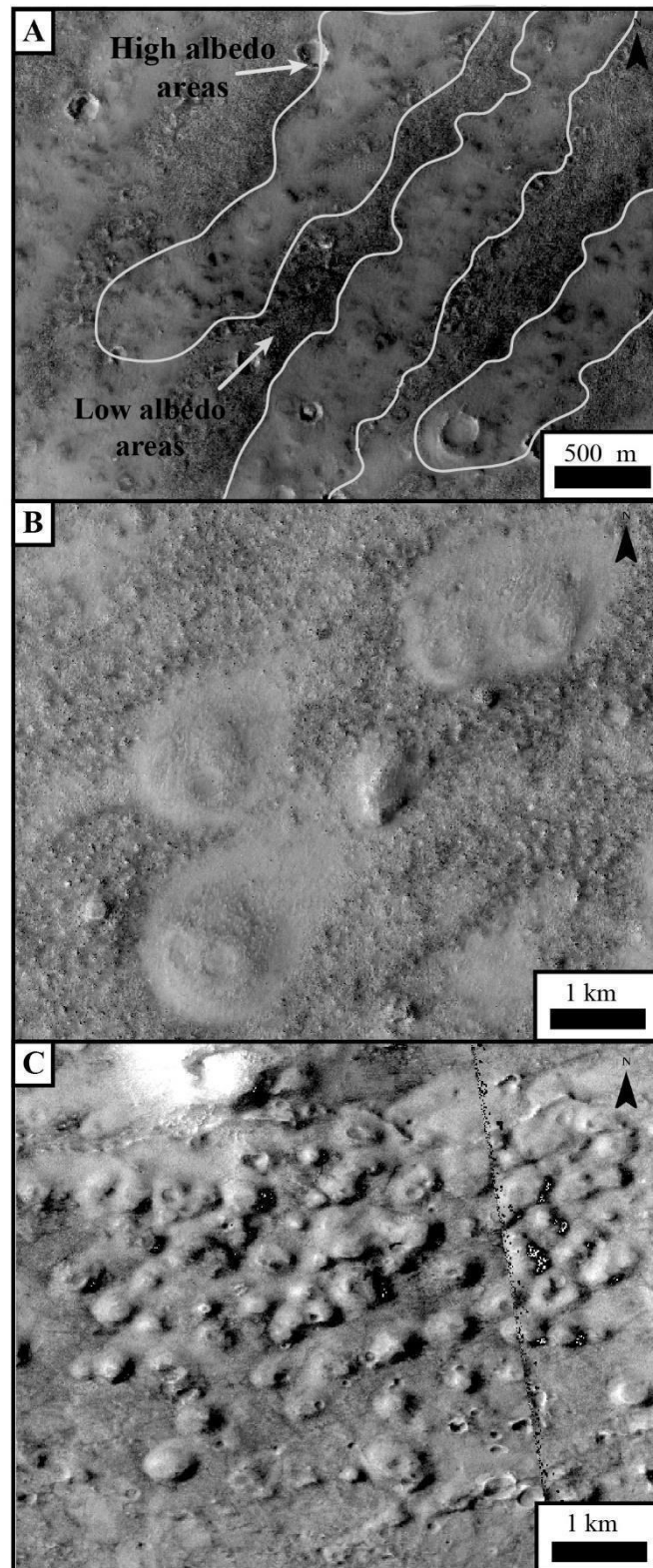
53 Thumbprint terrain was usually described as sets of alternating ridges/mounds and  
54 depressions, with high and low albedo respectively, up to several tens of kilometres in  
55 length (Fig. 1A; Lockwood et al., 1992). However, we observed no noticeable variations  
56 of alternating relief by using MOLA laser shots in our study area (Fig. 3). The low albedo  
57 surfaces show a darker rough surface, while the high albedo areas show alignments of  
58 poorly expressed mounds (Fig. 4A) that can individually be dome-like (Fig. 4B) or more  
59 rarely conical (Fig.4C) when seen at high resolution.



61

62

63 *Figure 3. Topography of the thumbprint terrain. A topographic profile crossing the high and low albedo*  
 64 *area was performed by using MOLA laser shots. No clear topographic alternation is observed between*  
 65 *the two areas. The black points represent the approximate size of the laser shot on the surface (128m)*  
 66 *according to Smith et al., 1999; 2001 (CTX image n° B17\_016195\_2250). North is oriented 90 degrees*  
 67 *right. Courtesy of NASA/ JPL/Univ. of Arizona.*

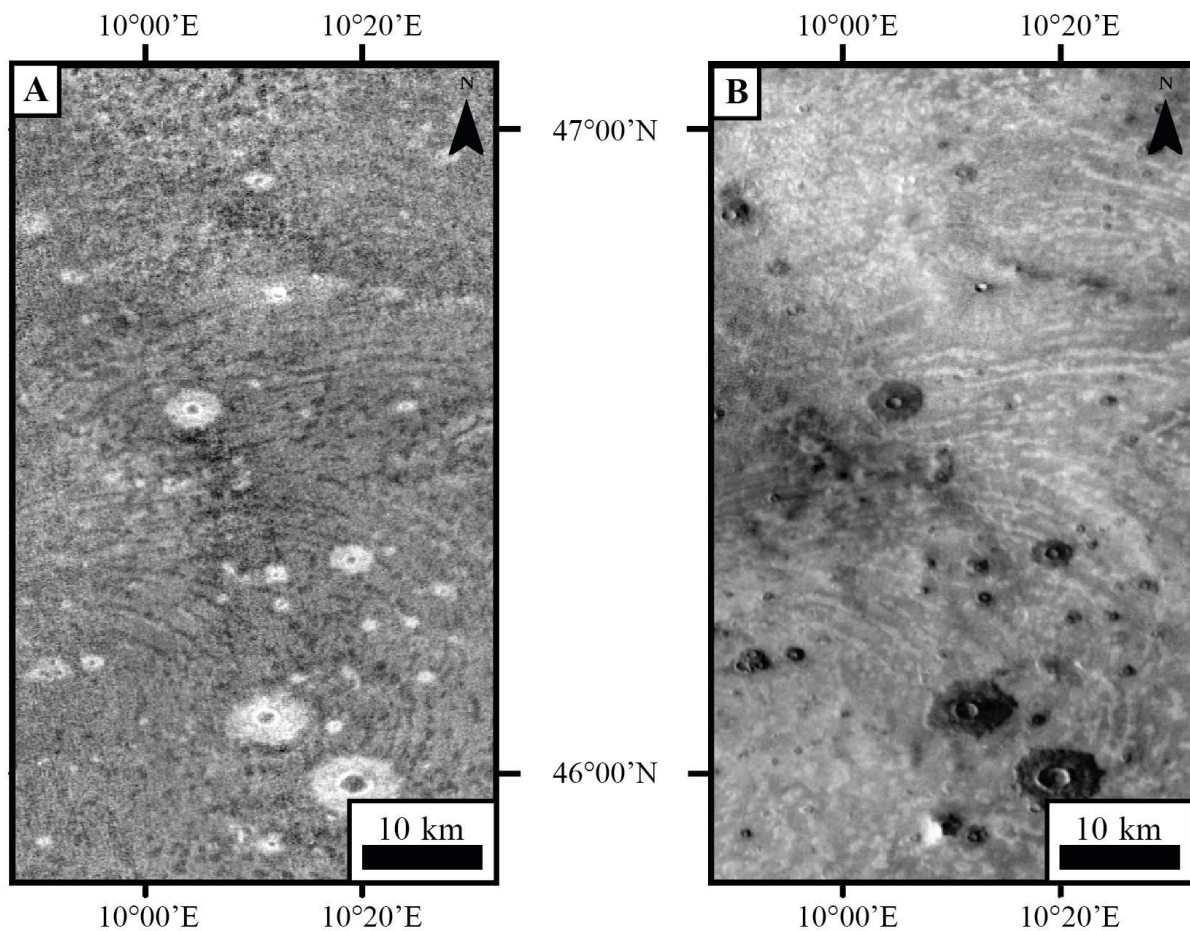


68

69 *Figure 4. Morphology of thumbprint terrain at high resolution. A) High albedo areas include mounds and*  
 70 *pits while low albedo areas are composed of a rough surface (HiRISE image: ESP\_011949\_2255). The*  
 71 *high albedo areas of the thumbprint terrain include mounds that may be B) dome-like (HiRISE image:*  
 72 *PSP\_001928\_2265) or more C) cone-like shaped mounds (CTX image: P22\_009747\_2239). The former*  
 73 *type is usually bigger in diameter than the latter, but no clear correlation was found. Courtesy of JPL/Univ.*  
 74 *of Arizona.*



75 Thermal inertia comparisons showed that thumbprint terrain is brighter than the  
 76 surrounding terrain in day-time THEMIS images, whereas it is darker in night-time ones  
 77 (Fig. 5). Moreover, the whole lobate TT unit is also generally brighter in day-IR images  
 78 in comparison to the surrounding plains and plateau units, so we readily defined the  
 79 lobate TT unit limit realizing: (i) TT is also present in the ABvm unit, although previous  
 80 literature (Tanaka et al., 2005) considers that it extends only within the ABvi unit (Fig. 2)  
 81 and (ii) it covers an extensive surface greater than  $10^5$  km<sup>2</sup> in southeastern Acidalia  
 82 Planitia.

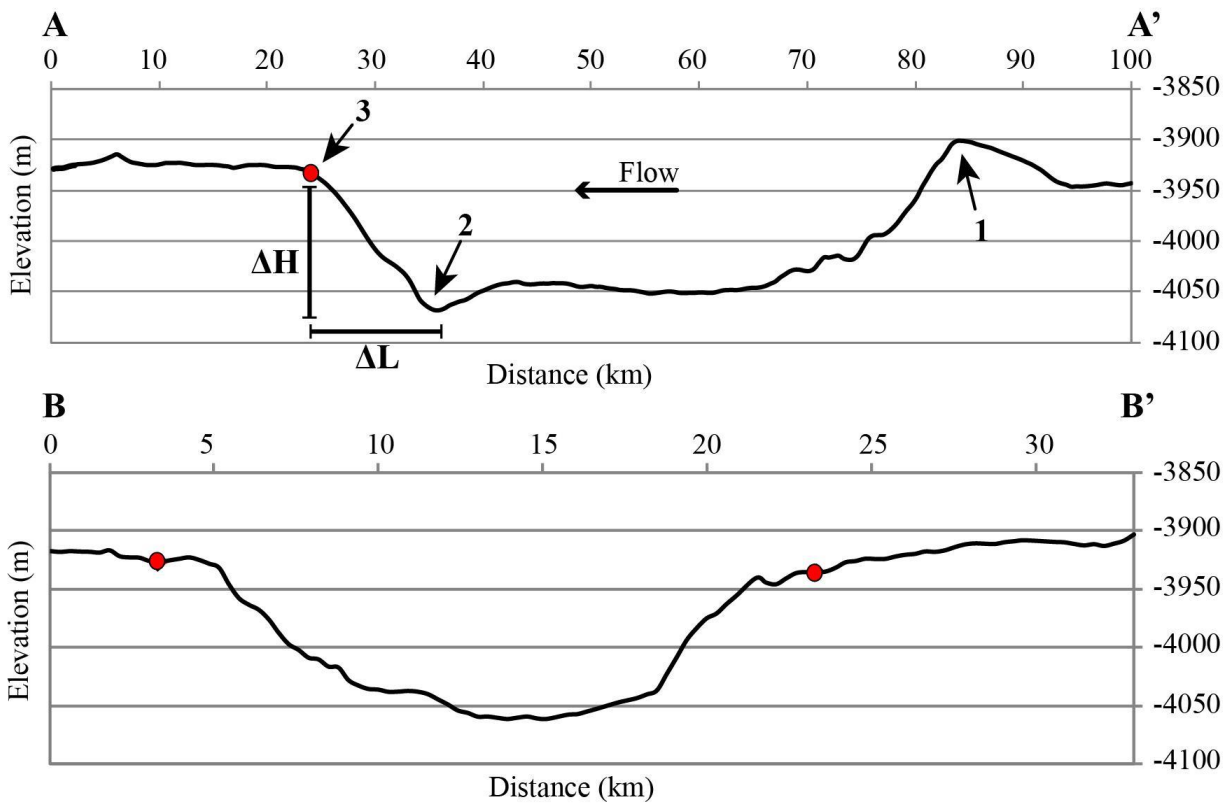
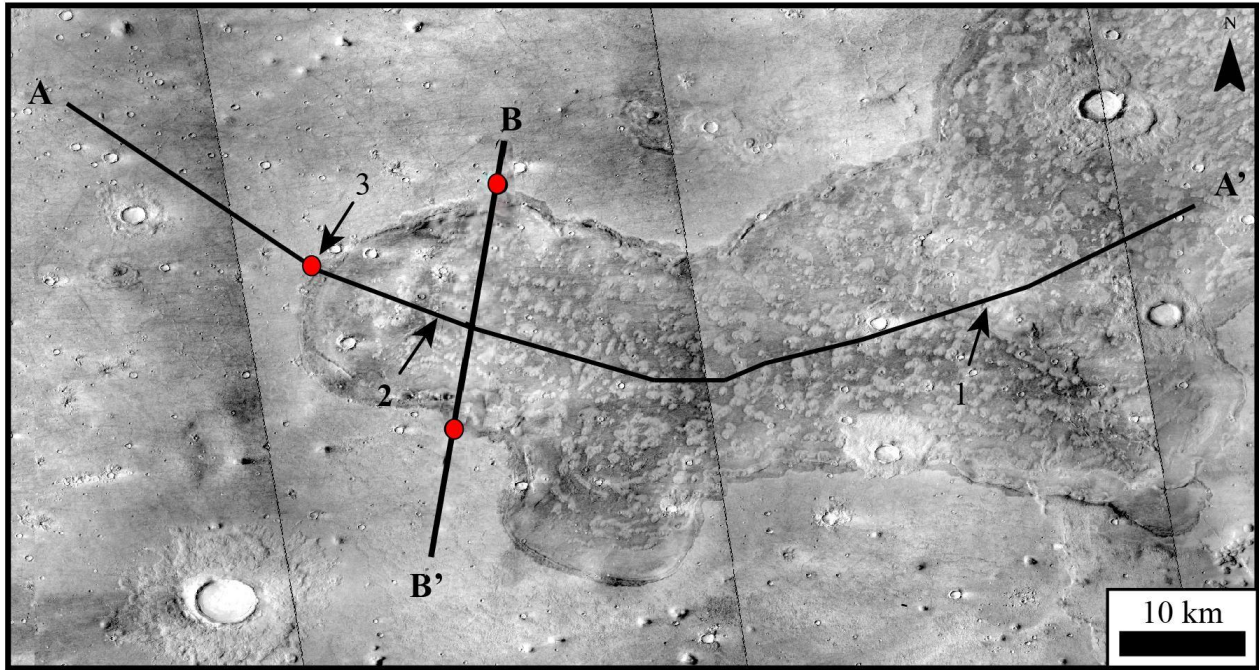


83  
 84 *Figure 5. THEMIS daytime and night-time infrared images of thumbprint terrain. The low albedo areas are*  
 85 *darker in night-time images (A) and brighter in daytime ones (B). Night-time image resolution is lower than*  
 86 *the daytime resolution.*

87 Unfortunately, the northern limit of the lobate TT unit in Acidalia Planitia is covered by a  
 88 unit of lower albedo that has a constant elevation of around -4100m (supplementary  
 89 material). Therefore, the true extent of the unit remains unknown. In the southern region  
 90 of the study area, the lobate TT unit covers the plateau and valleys near the dichotomy.  
 91 The southern boundary of the unit is marked by several lobate features with peripheral  
 92 and lateral ridges that sometimes overlap each other in the Deuteronilus valley system

93 (Costard et al., 2017). The lobes are found inside valleys or on lateral valley plains  
94 between -3860 m and -4001 m altitude.

95 We also observed that lobes are oriented upslope of few degrees (Fig. 6), or on residual  
96 hills plains (Fig. 7), reaching a maximum thickness of 10-20 m by using MOLA laser  
97 shots (Costard et al., 2017). Occasionally, the characteristic alignments of  
98 cones/mounds tend to distance themselves approaching the edge of the lobate TT unit  
99 and do not show the characteristic high albedo small mound chains. Regardless, we  
100 included them in the thumbprint terrain unit due to thermal inertia comparisons with  
101 surrounding areas, lateral continuity and sparse presence of clusters or individual small  
102 mounds. A general southeastward trend has been computed from the analysis of the  
103 high albedo mounds (Fig. S1 - supplementary material), even if there are some lobes  
104 with random direction because of first-order topographic influence (Fig. S2 -  
105 supplementary material).

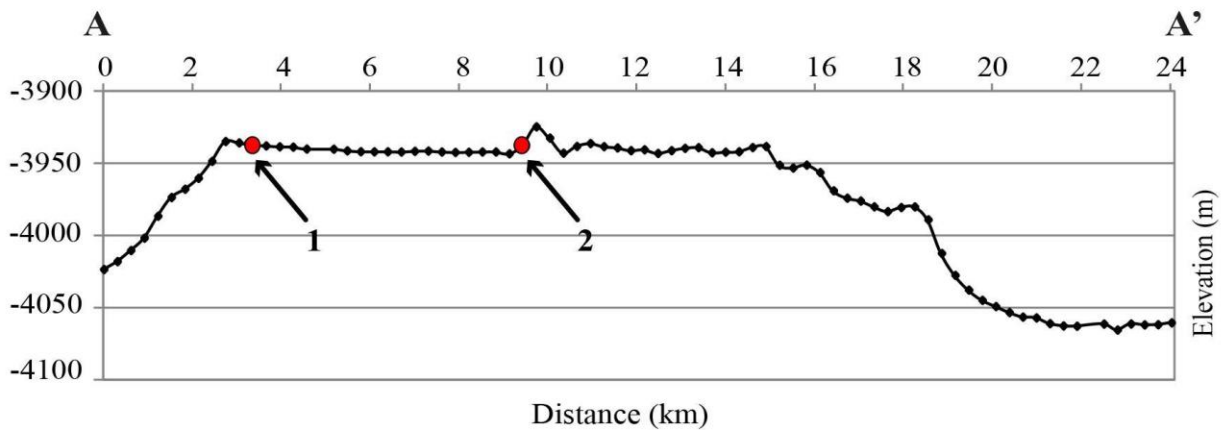
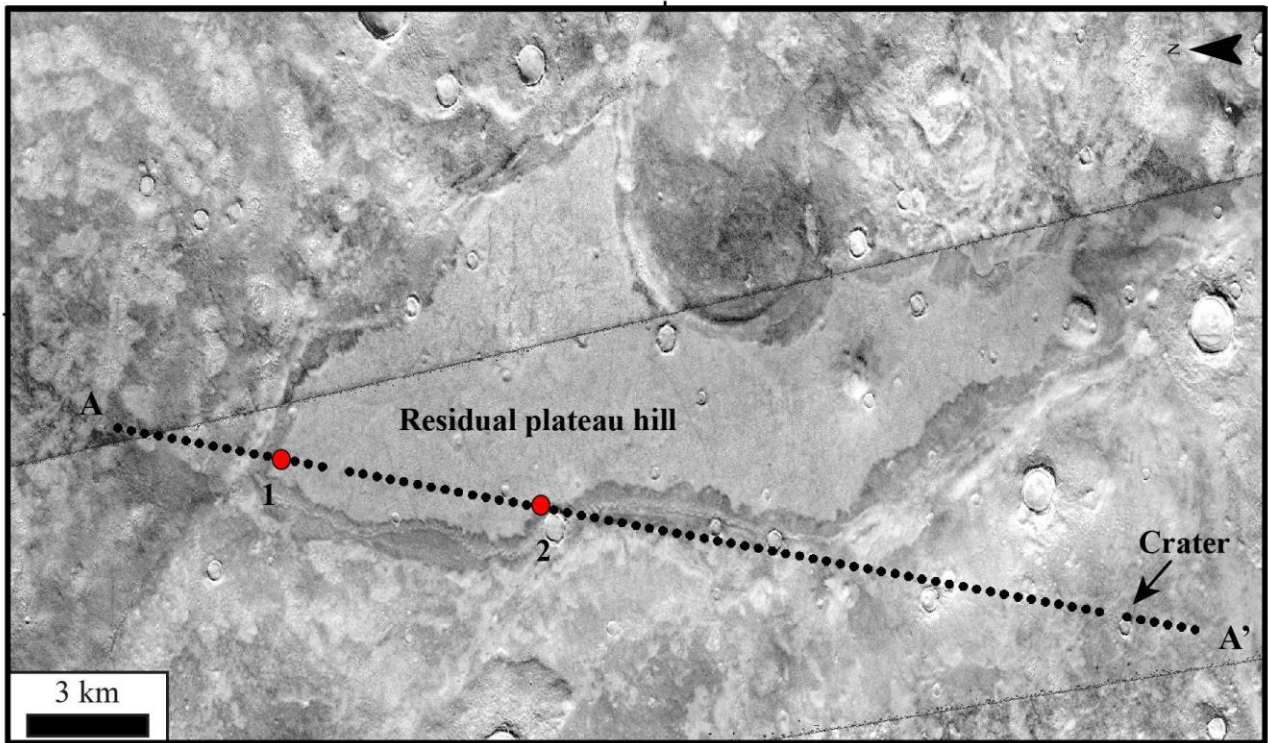


106

107

108 *Figure 6. Longitudinal profile (A-A') and cross-section (B-B') of a southern limit lobate TT unit deposit from*  
 109 *MOLA DEM.  $\Delta L=12000\text{m}$ ;  $\Delta H=138\text{m}$ . Lobate TT unit limits are marked by red dots on the image and on*  
 110 *profiles as well. Relative slope value is  $\approx 0.70^\circ$ . CTX images: P18\_008112\_2251; P18\_007901\_2250;*  
 111 *P18\_008046\_2253; P21\_009338\_2253.*



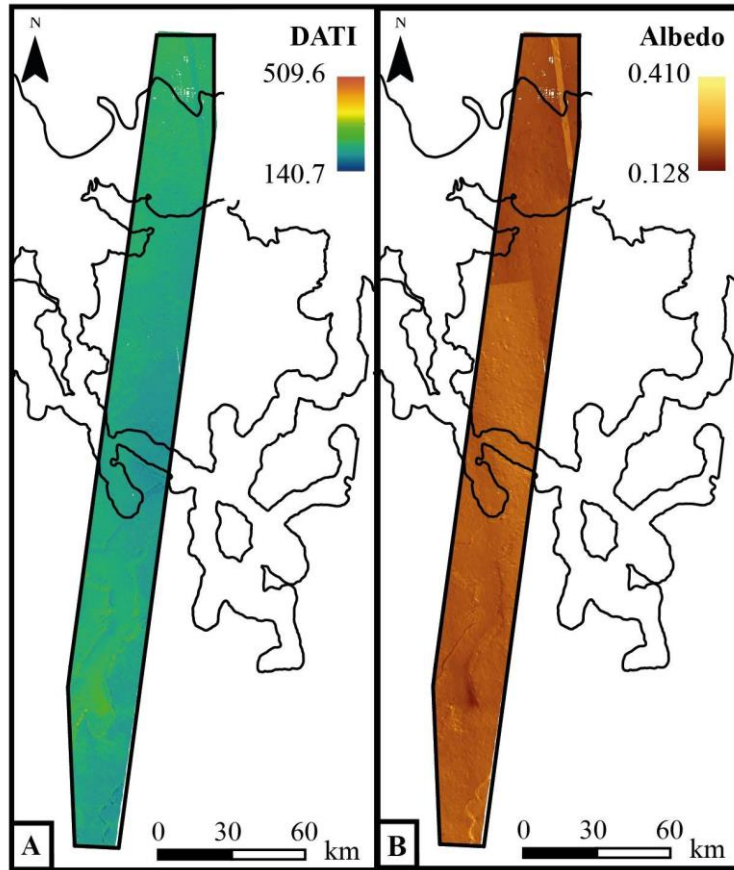


112

113 *Figure 7. Thumbprint terrain deposits can move upslope reaching plateau residual hills. Thumbprint*  
 114 *terrain limit that is marked by red dots on the image and on A-A' MOLA shots profile as well (CTX image:*  
 115 *B02\_010261\_2248). North is oriented 90 degrees left.*

116 Thermal inertia was calculated based on the IR THEMIS data for the part of the  
 117 thumbprint terrain unit (marked by the black line on Fig. 8A). For this area, DATI values  
 118 ranges from 171 to 311 indicating fine particles (~40 – 500  $\mu\text{m}$ : silt to medium sand)  
 119 with the average particle size of 125  $\mu\text{m}$  (Ferguson et al., 2006; Wentworth, 1922). An  
 120 average albedo of 0.19 (range 0.15-0.33) calculated for this region based on CTX  
 121 images further supports the presence of silt and fine sand. (Fig. 8 B).

122



123

124 Figure 8. Thermal inertia analysis. A) DATI ( $J m^{-2} K^{-1} s^{-1/2}$ ) values for the selected part of the study area  
 125 shown in Fig.2. B) albedo values. Lobate thumbprint terrain unit extension is marked by the black line.  
 126 The location of Fig. 8 is also shown in Fig.2. Top-left corner coordinates:  $15^{\circ}39'58.366''E$ ;  
 127  $49^{\circ}41'20.171''N$ .

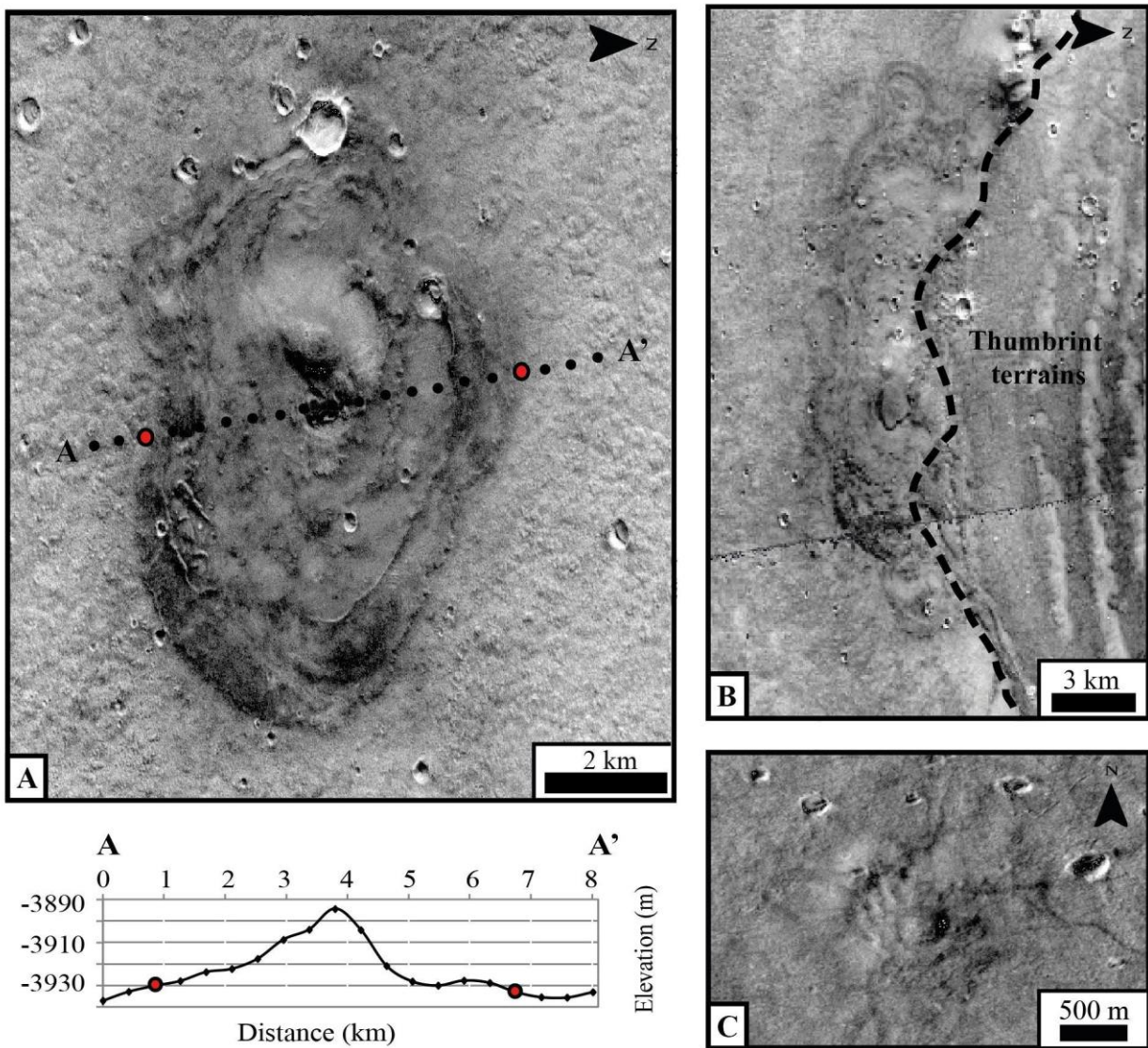
Material	DATI ( $J m^{-2} K^{-1} s^{-1/2}$ )	Particle diameters ( $\mu m$ )
Dust	~ 150	~ 45 (silt)
Sand	~ 200	~ 160 (very fine sand/fine sand)
	230-270	290 - 575 (medium sand)
Rock	1200	

128

129 Table 1. Comparative DATI values ( $J m^{-2} K^{-1} s^{-1/2}$ ) and particles diameters ( $\mu m$ ) of selected materials  
 130 (after Ferguson et al., 2006).

131 We observed several domes (10-12 kilometres in diameter) near or along the lobate TT  
 132 unit limit (Fig. 2), making their detection difficult inside thumbprint as the lobate TT unit  
 133 overlaps them (Fig. 9B). These morphologies are mostly elliptical, have an irregular and  
 134 lobate edge and show concentric features compared to the central peak (Fig. 9A; Fig.  
 135 9B). Smaller features ( $\approx 1$ km in diameter) are observed, but are almost circular and do

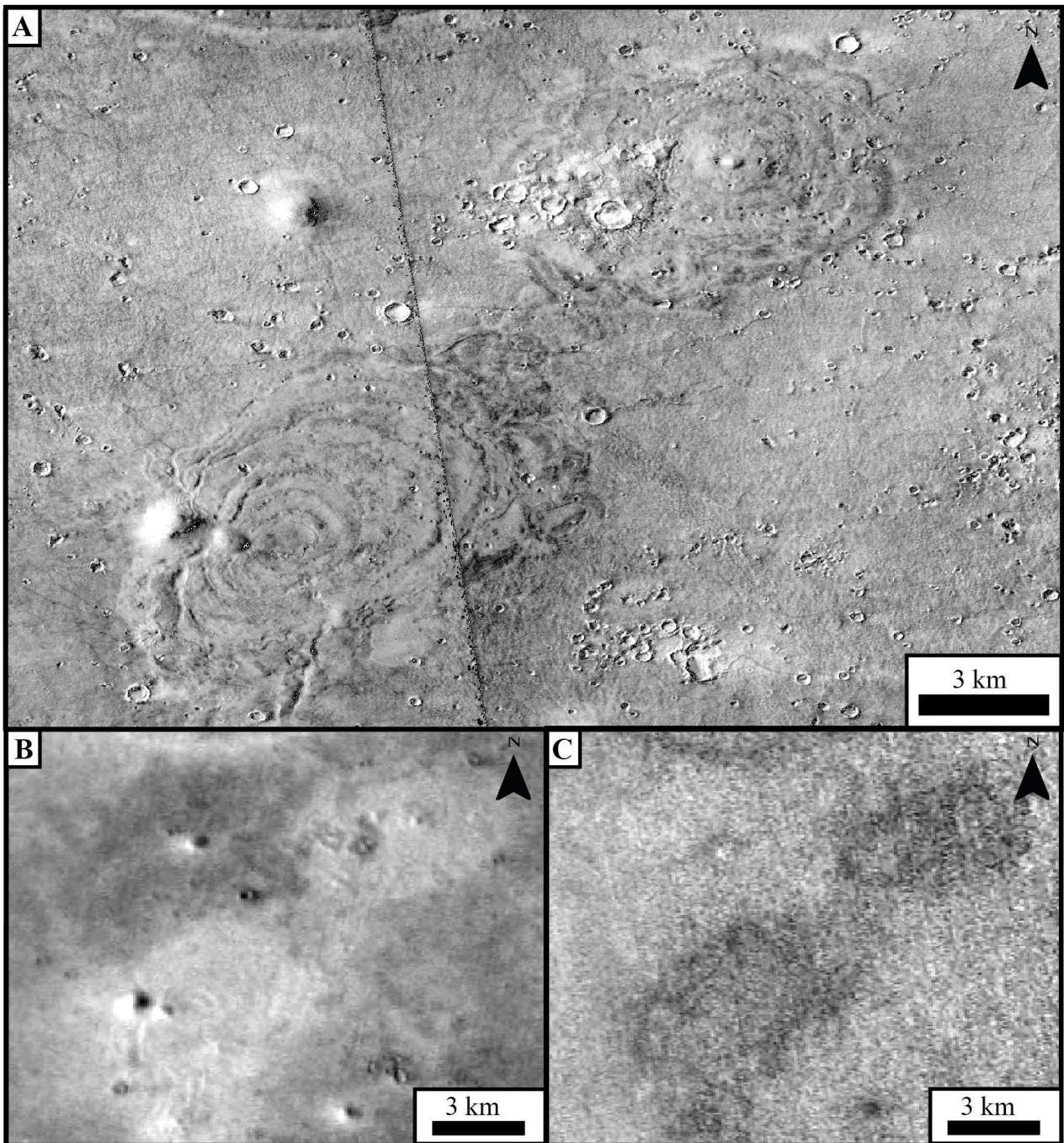
136 not show clear concentric lineaments (Fig. 9C). MOLA elevation profiles showed they  
 137 have a symmetric profile and heights of few tens of meters as shown in Fig. 9A.  
 138 Thermal inertia comparisons show that these domes are very bright in day-IR images  
 139 and darker in the night compared to the surrounding units (Fig. 10). This characteristic  
 140 is qualitatively similar to the response that thumbprint terrain has to night/day material  
 141 exposition. In fact, TT is also generally brighter in day-IR images, whereas it is darker  
 142 during night acquisition (Fig. 5).



143  
 144 *Figure 9. Large domes underlying thumbprint terrain unit. A) MOLA laser shot cross-section cutting a*  
 145 *dome that is found outside thumbprint terrain unit. Central peak and some relating concentric*  
 146 *features are visible. The edge is elliptical and quite regular. The boundary is marked by red dots.*  
 147 *Dome height is  $\approx 40$ m (CTX image: B17\_016195\_2250). North is oriented 90 degrees right. B) Dome*  
 148 *overlapped by thumbprint terrain. Black dashed line marks thumbprint terrain unit limit. Central peak,*  
 149 *some concentric features and an irregular and lobate edge are observed. (CTX image:*



150 P21\_009391\_2238). North is oriented 90 degrees right. C) Small circular dome that does not show a  
151 clear/regular limit or concentric features related to the centre (CTX image: G23\_027087\_2234).



152

153

154 *Figure 10. Large domes several kilometres across underlying thumbprint terrain unit in visible CTX-scale*  
155 *(A). Thermal inertia response in day- and night-time acquisitions. THEMIS images show that domes are*  
156 *brighter in daytime (B) and darker in night-time (C) compared to surrounding areas. Night-time image*  
157 *resolution is lower than daytime image. CTX images: P21\_009246\_2240; G23\_027087\_2234.*

158

159 **5 Discussion**

160 Since the most recent hypotheses have already provided a regional geological  
161 framework for lobate deposits in Acidalia Planitia (Rodriguez et al, 2016; Costard et al,  
162 2017; Costard et al., 2019 ), in the following paragraphs we will discuss and consider  
163 the characteristics of thumbprint terrain to each of the main geological scenarios (i.e.,  
164 pingoes, volcanic cones, liquefaction, mud-volcanoes, and tsunami-related deposits) in  
165 order to reconcile and insert TT origin in the regional context.

166 Although the scenario of a periglacial environment has been put aside in favour of more  
167 conceivable interpretations in the last years, Rodriguez et al. (2016) did not totally  
168 dismiss this hypothesis because tsunami deposits could have frozen and formed a layer  
169 of permafrost. Moreover, the presence of excess ejecta craters strengthens the  
170 occurrence of an icy sub-surface layer that could also be responsible for surficial  
171 geological processes as proposed for other geological processes in other areas on  
172 Mars (Salese et al., 2016). However, pingoes are domical structures formed by freezing  
173 and swelling of groundwater and are, therefore, composed by the same material as their  
174 surroundings. Thus, the difference observed between the pitted mounds and the darker  
175 adjacent areas in THEMIS images are not consistent with a pingo hypothesis (Fig. 5).  
176 Furthermore, the growth of pingoes is accompanied by radial extension cracks (Mackay,  
177 1973; 1998), which were not observed in any of our target features and deposits. The  
178 high albedo mounds have been also interpreted as moraines, or ice-cored ridges  
179 associated with a former glacial environment (Lucchitta, 1981; Rossbacher and Judson,  
180 1981; Farrand and Gaddis, 2003), but their exact origin is still under debate. Herein, we  
181 find the periglacial origin hypothesis problematic because of thermal inertia  
182 comparisons with surrounding deposits (Fig. 5), material viscous behaviour that is not  
183 consistent within a periglacial or glacial environment, and the lack of typical glacial  
184 features such as polygons, cracks, eskers, drumlins and kettle holes.

185 Alternatively, over many decades, the associated underlying TT lobate deposits have  
186 also been interpreted as lava flows flooded over a broad region forming a volcanic plain.  
187 In this scenario, the high albedo mounds are interpreted in a variety of ways including:  
188 1) rootless cones (pseudocraters) formed by explosions that resulted from a lava flow  
189 advancing over a wet substrate (Frey and Jarosewich, 1982); 2) cinder cones formed by  
190 explosion and deposition of ashes (Wood, 1979); or 3) tuff cones resulting from the  
191 explosive interaction between rising magma and water/groundwater (Wohletz and  
192 Sheridan, 1983). However, thumbprint terrain mounds are brighter than basaltic sands

193 in Acidalia (Farrand et al., 2005) and the DATI values of the TT are much lower than the  
194 ones expected for lava flows (Fig. 8; Table 1). In addition, volcanic cones do not form in  
195 arrangements that resemble patterns observed within TT. Based on the lack of these  
196 conditions, we conclude that a volcanic origin of the thumbprint terrain is unlikely for TT  
197 in southeastern Acidalia Planitia.

198 More recently, thumbprint terrain has also been interpreted as mud volcanoes which  
199 formed after the freezing of an ancient standing body and/or rapid sedimentation and  
200 diagenesis. The existence of a mud sheet flood has also been proposed for the northern  
201 lowlands due to some hills and ground undulations in Isidis Planitia and Mare Australe  
202 (Farrand et al., 2005; Oehler and Allen, 2010; Souček et al., 2015; Komatsu et al.,  
203 2016). As outflow channels filled northern lowlands (Baker et al., 1991; Carr and Head,  
204 2003), the following ice sublimation mostly depended on the accumulation rate of debris  
205 on the surface. Sublimation residue would have formed the Vastitas Borealis Formation  
206 units. Even a shallow layer of little debris thickness would have decreased sublimation  
207 and favoured freezing (Farmer and Doms, 1979; Carr, 1990; Carr and Head, 2003):  
208 both the gradual freezing and the load of the top debris layer make the internal pressure  
209 rise. This could have led to mixtures of water, ice, rock/soil and mud expulsion on the  
210 surface as proposed in Utopia Planitia in order to explain etched flows and polygonal  
211 troughs (Ivanov et al., 2014). This model can also be applied to the thumbprint terrain in  
212 Acidalia Planitia since geologic observations and settings are similar. The high albedo  
213 mounds could be analogous to terrestrial mud volcanoes with a wide range of different  
214 features from meter sized cones to domical structures hundreds of meters in size  
215 (Kholodov, 2002) that are similar in lateral and vertical dimension to the Martian domes  
216 and cones of the Acidalia region. However, thermal inertia and albedo values indicate a  
217 widespread presence of fine sand and silt (mud?) size grains. The reason could be  
218 explained by two fundamental factors that eventually interacted with each other. First,  
219 detectable grain-size values might not match mud particle size anymore since the  
220 material dried up and got indurated over the time. Ultimately, sandy mud volcanoes  
221 have been found on Earth (Miyakawa et al., 2013) and, thus, this phenomenon cannot  
222 be excluded either.

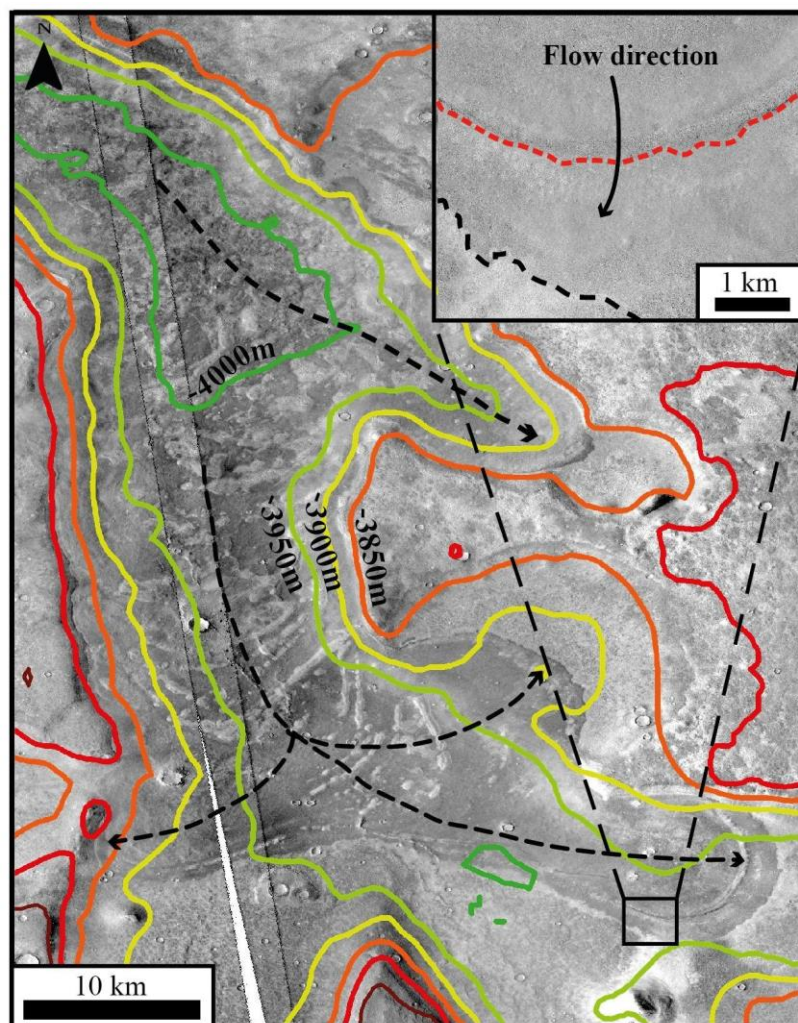
223 Furthermore, we need to take into account the coexistence of TT with lobate underlying  
224 deposits which points to flows with a certain viscosity: the lobate deposits with  
225 peripheral ridges clearly indicate that viscous material flowed inside southern valleys

226 (Fig. 6; Fig. 11; supplementary material) and that the plateau and hills were partially  
227 flooded (Fig. 7; Fig. S1- supplementary files). Additionally, parallel and arcuate  
228 alignments of mounds/cones (thumbprint terrain) observed together around obstacles  
229 as knobs, residual hills, and plateaus (Fig. 1A, white arrow, Fig. S1- supplementary  
230 files), perfectly follow the inferred underlying lobate deposits flow direction (Fig. 11, Fig.  
231 S1 and Fig. S2- supplementary material). In the occurrence of an impact-generated  
232 tsunami: obstacles might have first influenced flow direction and speed (tsunami wave  
233 fronts), forming thumbprint terrain in parallel and curvilinear patterns. Nevertheless, an  
234 impact-generated tsunami provides an explanation to the main concern about the  
235 energy required to flow up slopes and reach topographic heights. In a previous work,  
236 three craters (30-50 km in diameter) were proposed (Fig. S3 - supplementary files) as  
237 the sources of the tsunami events, based on validated terrestrial models scaled to Mars  
238 (wave height, propagation, run up elevation, and distance) (Costard et al., 2017). The  
239 numerical tsunami simulations presented in Costard et al. (2017) link the TT alignments  
240 to interference patterns produced from the interaction between the tsunami fronts and  
241 the coastal topography. By binding the numeric simulation results to the morphological  
242 observations, we assert that a tsunami event contributed to the formation of TT mud-  
243 volcanoes.

244 On Earth, tsunamis move landward in a series of wave fronts (Lavigne et al., 2009),  
245 whose energy and interaction with the shoreline topography results in different  
246 inundation distances and distributions of lobate debris. Within the complex topography  
247 of flat-floored valleys and plateaus along the Martian dichotomy boundary, the  
248 interference of the multiple reflected and refracted waves that are observed in  
249 simulations explain the flow distribution itself and the origin of the arcuate and parallel  
250 pattern that characterizes the thumbprint terrain. Thumbprint terrain cones are not  
251 observed in any terrestrial tsunami, but they are herein considered mud volcanoes that  
252 formed as a consequence to an overpressure caused by rapid compaction upon  
253 deposition of the transported material during the final stage of a tsunami. A similar  
254 geological process was proposed for the emplacement of the Vastitas Borealis  
255 Formation in both Chryse and Acidalia Planitia at the regional scale (Salvatore and  
256 Christensen, 2014). According to this hypothesis, the Vastitas Borealis Formation would  
257 be a product of extensive sedimentary modification both during and immediately after  
258 outflow channel activity. Mud-extrusion would then result from burial and rapid



259 compaction of previously saturated deposits (Salvatore and Christensen, 2014). In our  
 260 study area, rapid compaction could have expelled a mixed water-mud material,  
 261 preferentially along the front, and would explain 1) the arcuate or random pattern of  
 262 thumbprint terrain reflecting the tsunami propagation when influenced by obstacles (Fig.  
 263 1A - white arrow) or not (Fig. 1A - black arrow), respectively and 2) the gradual  
 264 disappearance of TT cones toward the unit boundary as compaction, and hence  
 265 overpressure, should have decreased as the tsunami wave propagation progressively  
 266 lost energy and material while moving 'landward'.



267

268

269 *Figure 11. Lobes flow direction inferred from mounds alignments as marked by dashed black arrows.*  
 270 *Contour lines are 50 meters spaced. They show that flows clearly go upslope. g18\_025425\_2271;*  
 271 *b18\_016498\_2264. Inset: Thumbprint terrain flow exceeding valley scarp (dashed red line) for several*  
 272 *kilometers. Unit limit is marked by the red dashed line. The lobe has no peripheral ridges and its front is*  
 273 *lobate (HiRISE ESP\_016498\_2265).*

274 On Earth, geophysical surveys and studies - across the continental margins of the Arctic  
 275 Ocean – continuously detect suites of hectometre/meter-wide seafloor mounds



276 accompanied with seepage due to the destabilization of gas hydrates (methane)  
277 trapped in seafloor and permafrost-associated sediments (Serov et al., 2015, 2017;  
278 Andreassen et al., 2017). Pressure is increased by released methane and triggers  
279 blowouts through weakened zones. The Holocene marine transgression affected the  
280 Arctic shelves and led to an extensive permafrost thawing; this is the reason why gas  
281 hydrate degradation occurs primarily on the circum-Arctic Ocean continental shelves  
282 (Macdonald, 1990; Lachenbruch, 1994; Maslin, 2010), where subsea permafrost  
283 thawing and methane hydrate dissociation have been triggered by warming and  
284 inundation since the Late Pleistocene. Seafloor mounds are steep-sided, up to 1100 m  
285 wide, generally semi-circular to elliptical in plan view, and have an irregular upper  
286 surface incised with straight or curved furrows. Since the mounds are elevated well  
287 above the surrounding seafloor, the most plausible formation mechanism is either  
288 deposition or uplift. However, the absence of any discernible seismic paleo-seafloor  
289 favours the former hypothesis (Andreassen et al., 2017). We find it difficult to attribute  
290 thumbprint terrain cones in Acidalia Planitia to these terrestrial shallow-water sea-  
291 mounds considering the scale, mutual geographic distribution, timing of formation and  
292 their absence in any terrestrial tsunami deposit since these Martian cones are smaller  
293 and more densely coalesced (whether organized or not) than Earth's features.  
294 Therefore, TT mounds/cones are more likely thought as mud-volcanoes related to a  
295 catastrophic event (tsunami) rather than a release of pressure that gradually  
296 accumulated in the sub-surface due to sediment deposition. However, these terrestrial  
297 gas blowouts cannot be ruled out for elliptical domes that have been observed outside  
298 or under the thumbprint terrain unit (Fig. 2; Fig. 9) and must be further investigated to fit  
299 the Acidalia Planitia thumbprint terrain and tsunami-related deposit. The same  
300 qualitative thermal inertia response to daily temperature changes between elliptical  
301 domes and thumbprint terrain mounds indicates that: 1) these features might be  
302 composed by the same material reflecting the uniformity of lithologies in Acidalia  
303 Planitia and 2) both elliptical domes and high albedo mound thumbprint terrain  
304 alignments are qualitatively finer grained or more poorly consolidated than surrounding  
305 areas. This behaviour fits well with average DATI values and conclusion (see section 4).  
306 Therefore, elliptical domes may be the result of material extrusion (due to gradual  
307 freezing and/or the load of top debris) prior to the extensive viscous flowing (tsunami  
308 event) that led to the thumbprint terrain unit overlapping them and making dome  
309 detection difficult inside the lobate TT unit.

310 New findings stated that some TT is too young to have experienced the ocean floor  
311 environment, and, hence, a tsunami event, according to the current understanding of  
312 the cryosphere depth and thermo-chemical structure of Mars (De Toffoli et al., 2019).  
313 However, some areas of thumbprint terrain may be old enough to have experienced  
314 tsunamis. In De Toffoli et al., 2019, 370 Ma may be the age of a possible ice-rich mantle  
315 covering the older underlying TT deposit as it was observed in northern Arabia Terra  
316 where a similar thumbprint terrain is covered by young ice-rich ejecta from Lyot crater  
317 (48°33'42.72"N 18°12'46.78"E). Moreover, when dating surfaces and bedforms, it has  
318 been observed that the floor ages of some Martian outflow channels generally equate to  
319 younger mesoscale flows (several hundred meters to a few kilometers) instead of those  
320 published in more general geologic maps reflecting older and regional scale processes  
321 (Rodriguez et al., 2015). If alignments of cones in Acidalia Planitia were as recent as  
322 those analysed in Arcadia Planitia (De Toffoli et al., 2019), their strict occurrence with  
323 lobate flow deposits direction and highly organized patterns around obstacles (hills or  
324 residual plateaus), matching a very older and distinct tsunami event flow, would be an  
325 unusually fortunate coincidence. Consequently, this firmly underlines the importance of  
326 investigating thumbprint terrain found in other areas of Mars. High-resolution images  
327 may further distinguish multiple TT sets: i) analysing adjacent deposits and the  
328 geological context in which they are formed, ii) evaluating origin and/or putative trigger  
329 mechanisms discerning any morphological convergence.

330 The ocean hypothesis remains controversial and explanations have been put forward to  
331 account for the presence of the TT in the absence of an ocean. For example, Skinner et  
332 al. (2008) proposed that the propagation of seismic surface waves through northern  
333 plains sedimentary units could have triggered liquefaction and run-up flows along the  
334 margins of these deposits. In conclusion, given the morphology, the scale, the thermal  
335 inertia analysis, the strict occurrence of thumbprint terrain within lobate deposits and  
336 their congruous spatial arrangement with inferred lobes direction, and the significant  
337 energy required to surmount little slopes, here we favour a tsunami-related origin for TT  
338 in Acidalia Planitia, rather than simply a mud-volcanism deposit.

339

## 340 **6 Conclusions**

341 This paper renewed questions about the presence of a large standing body of water on  
342 Mars by analysing thumbprint terrain, lobate morphologies and deposits in southeastern

343 Acidalia Planitia. The most likely hypothesis is a tsunami-related origin, as lobate TT  
344 unit characteristics (e.g., viscosity, onslope flows, etc...), geological setting and numeric  
345 simulations are comparable to terrestrial tsunami deposits. Lobate deposits inside  
346 valleys, peripheral lobes and lateral ridges, as well as the energy required to surmount  
347 little slopes, overlap valley walls and reach the plateau, fit well with a viscous flow of fine  
348 material from the advance of a tsunami. Here, we interpret that these lobes are the  
349 remnant of an impact-induced flow with high energy that produced a large inundation  
350 subsequent to one or several tsunamis. In this context, thumbprint terrain would be  
351 related to the final stage evolution of the tsunami wave propagation, i.e. mud volcanoes  
352 that extruded water-mud mix material along the tsunami wave fronts. A wider coverage  
353 of high-resolution data would improve our understanding and reveal new crucial  
354 information in the ongoing debate of thumbprint terrain origin.

355 The presence (Parker et al., 1989, 1993; Head et al., 1998, 1999; Clifford and Parker,  
356 2001; Carr and Head, 2003; Tanaka et al., 2003, 2005), and eventual freezing (Ivanov  
357 et al., 2014), of a former northern body of water, or a mud-ocean as Jöns (1987)  
358 proposed, provides the geological context for thumbprint terrain as mud volcanoes  
359 related to a tsunami event. In addition, crater counting showed that lobate TT unit is  
360 Early Amazonian;  $2.8 \pm 0.2$  Gyr according to Hartmann 2004-iteration (Fig. S4 -  
361 supplementary files). This crater counting analysis is concordant to a crater-retention  
362 age of 2.9 Gyr, proposed by Costard et al., 2017 for the same area, and to other  
363 previous literature (Hiesinger et al. 2009) which corresponds to an Early  
364 Amazonian/Late Hesperian ocean, in agreement with Parker et al., 1993. The Late  
365 Hesperian is also the timing of peak outflow channel activity, and thus is consistent with  
366 the presence of a transient northern ocean ~3 Ga.

367 Giving morphologies and scales, fully thermal inertia and albedo values compliance,  
368 multiple impact craters possibility fitting numerical simulations, the occurrence of TT  
369 with lobes, their congruous alignments with inferred lobes direction and in favour of a  
370 general geological context, we herein mainly support the tsunami-driven mud-volcanoes  
371 hypothesis rather than others mentioned above.

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381

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