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# Possible crater-based pingos, paleolakes and periglacial landscapes at the high latitudes of Utopia Planitia, Mars

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## Accepted Manuscript

Possible crater-based pingos, paleolakes and periglacial landscapes at the high latitudes of Utopia Planitia, Mars

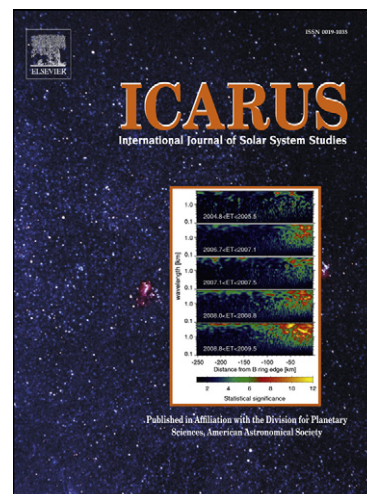
R.J. Soare, S.J. Conway, G.D. Pearce, J.M. Dohm, P.M. Grindrod

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3 **Possible crater-based pingos, paleolakes and periglacial landscapes at**  
4 **the high latitudes of Utopia Planitia, Mars**  
5

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31 **Pages:** 28

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34 **Abstract**

35 Closed-system pingos (CSPs) are perennial ice-cored mounds that evolve in relatively  
36 deep and continuous permafrost. They occur where thermokarst lakes either have lost or are  
37 losing their water by drainage, evaporation or sublimation and form by means of freeze-thaw  
38 cycling, permafrost aggradation and pore-water migration. The presence of CSPs on Mars,  
39 particularly on late-Amazonian Epoch terrain at near-polar latitudes, would indicate: 1. the  
40 antecedent occurrence of ponded water at the mound-formation sites; 2. freeze-thaw cycling of  
41 this water; and, 3. boundary-conditions of pressure and temperature at or above the triple point of  
42 water much more recently and further to the north than has been thought possible.

43 In 2005 we studied two crater-floor landscapes in northern Utopia Planitia and used  
44 MOC narrow-angle images to describe mounds within these landscapes that shared a suite of  
45 geological characteristics with CSPs on Earth. Here, we show the results of a circum-global  
46 search for similar crater-floor landscapes at latitudes  $> 55^{\circ}\text{N}$ . The search incorporates all  
47 relevant MOC and HiRISE images released since 2005. In addition to the two periglacially  
48 suggestive crater-floor landscapes observed by us earlier, we have identified three other crater  
49 floors with similar landscapes. Interestingly, each of the five mound-bearing craters occur within  
50 a tight latitudinal-band (  $64\text{-}69^{\circ}\text{N}$ ); this could be a marker of periglacial landscape-modification  
51 on a regional scale.

52 Just to the north of the crater-based pingo-like mounds Conway et al. (2012) have  
53 identified large (km-scale) crater-based perennial ice-domes. They propose that the ice domes  
54 develop when regional polar-winds transport and precipitate icy material onto the floor of their  
55 host craters. Under a slightly different obliquity-solution ice domes could have accumulated at  
56 the lower latitudes where the putative CSPs have been observed. Subsequently, were

57 temperatures to have migrated close to or at 0°C the ice domes could have thawed, forming  
58 endogenic paleolakes. This region also contains a significant concentration of crater-floor  
59 polygons. The polygons are thought to have formed by desiccation (El Maarry et al., 2010, 2012)  
60 or thermal contraction (Soare et al., 2005); on Earth each of these processes is associated with  
61 the end-stage of lake evolution.

62 On the basis of our enhanced image collection, a new map displaying the global  
63 distribution of mound-bearing craters and a two new digital-elevation models of a crater-floor  
64 with pingo-like mounds, we evaluate the CSP hypothesis anew. We also explore two  
65 alternative hypotheses: 1. the mounds are weathered central-uplift complexes; or, 2. they are  
66 impact-related hydrothermal structures. However, we propose that the CSP hypothesis is much  
67 more robust than these alternatives, encompassing geomorphological, cartographical,  
68 stratigraphical and climatological observations, and less subject to inconsistencies.

69 **Key words:** Mars climate, polar geology, surface

## 70 *1. Introduction*

71 Closed-system (hydrostatic) pingos (CSPs) are perennial ice-cored hills or mounds. They  
72 evolve and persist only in permafrost, i.e. ground that is frozen for periods of no less than two  
73 years, that is continuous and relatively deep (Washburn, 1973; Harris et al., 1988; Mackay, 1998;  
74 French, 2007). CSPs are tens of metres in height and have basal diameters that reach hundreds of  
75 metres in some instances (**Fig. 1**). Their shape ranges from circular to sub-circular to elongate  
76 (**Fig. 1**). Other landforms such as small-sized polygons ( $\leq 40\text{m}$  in diameter) (**Fig. 2g**) formed by  
77 means of thermal-contraction cracking, and polygon-trough/junction pits, often are observed in  
78 close spatial-association with CSPs (Washburn, 1973; Mackay, 1998; French, 2007) (**Fig. 2b**).

79 On Earth, CSPs occur in regions such as the Tuktoyaktuk Coastlands (TC) of northern  
80 Canada where thermokarst lakes either have lost or are losing their water by drainage,  
81 evaporation or sublimation (e.g. Harris et al., 1988; Mackay, 1998) (**Figs. 2a-e; f-h**). They are  
82 the product of seasonal freeze-thaw cycling (as are the ice-wedges that underlie the small-sized  
83 polygons with which they may be associated spatially), permafrost aggradation and soil-moisture  
84 (pore-water) migration (Washburn, 1973; Mackay, 1998; French, 2007).

85 The identification of closed-system pingos on Mars, particularly on late-Amazonian  
86 Epoch terrain at or near-polar latitudes would point to: 1. the antecedent occurrence of ponded  
87 water at the mound-formation sites; 2. freeze-thaw cycling of this water; and, 3. boundary-  
88 conditions of pressure and temperature at or above the triple point of water much more recently  
89 and further to the north than many workers have thought possible.

90 In 2005 a small set of narrow-angle MOC (Mars Orbiter Camera, Mars Global Surveyor)  
91 images were used to describe two crater-floor landscapes in northern Utopia Planitia (UP) that  
92 showed mounds with morphological characteristics and landform associations similar to the  
93 CSPs of the TC (Soare et al., 2005a; 2005b). The images covered only a part of the crater floors.  
94 Using all relevant HiRISE (Mars Reconnaissance Orbiter, High Resolution Imaging Science  
95 Experiment) and MOC images (not available at the time of our earlier work and exhibiting  
96 complete crater-floor coverage) we have performed a circum-global search for similar crater-  
97 floor landscapes at latitudes  $> 55^{\circ}\text{N}$ . Three other crater floors that show similar landscapes have  
98 been identified. Interestingly, all of the mound-bearing craters are located within a tight  
99 latitudinal-band (  $64\text{-}69^{\circ}\text{N}$ ), centred in northern UP (**Fig. 3, Table 1**). This could be a marker of  
100 landscape-modification on a regional scale.

101 Just to the north of the pingo-like mounds Conway et al. (2012) have identified large  
102 (km-scale) crater-based perennial ice-domes in a near-polar latitudinal band ( $\sim 70^\circ\text{N}$ ). They  
103 propose that the ice domes are the product of regional polar-winds that transport and precipitate  
104 icy material onto the floor of their host craters. Under a slightly different obliquity-solution the  
105 same process could have occurred further to the south, in those craters where the putative closed-  
106 system pingos have been observed. Subsequently, were temperatures to have migrated close to or  
107 at  $0^\circ\text{C}$  the ice domes could have thawed, forming endogenic paleolakes. This region also  
108 contains a significant concentration of crater-floor polygons with diameters  $\leq 350\text{m}$ . The  
109 polygons are thought to have formed by desiccation (El Maarry et al., 2010, 2012) or thermal  
110 contraction (Soare et al., 2005); on Earth, each of these processes is associated with the end-stage  
111 of lake evolution.

112 Using an enhanced image collection, a new map displaying the global distribution of  
113 mound-bearing craters and two new digital-elevation models of a crater-floor with pingo-like  
114 mounds, we evaluate the CSP hypothesis anew. We also explore two alternative hypotheses: 1.  
115 the mounds are weathered central-uplift complexes; or, 2. they are impact-related hydrothermal  
116 structures.

## 117 **2. Methods**

118 As noted in the introduction, Soare et al. (2005a, b) employed narrow-angle MOC images  
119 ( $\sim 3\text{-}6\text{m/pixel}$ ) to identify, discuss and map two crater-floor landscapes with putative CSPs in  
120 northern UP. At the time, narrow-band and high-resolution image coverage of the study region -  
121  $55\text{-}70^\circ\text{N}$  and  $60\text{-}120^\circ\text{E}$  - was incomplete. Thus, there were significant gaps in our map and  
122 intriguing as the CSP hypothesis appeared to be, its validation was beyond the compass of  
123 available data.



124 Now, all of the relevant MOC and HiRISE images of this region that were not available  
125 in 2005 are integrated with the more continuous impact-crater data collected by Conway et al.  
126 (2012) from MOLA (Mars Orbiter Laser Altimeter, Mars Global Surveyor) coverage. Moreover,  
127 we use all available HiRISE images (30-60cm/pixel) to extend the longitudinal reach of our  
128 study zone from a regional perspective to a circumpolar one (i.e., from 60° of coverage to 360°).  
129 Within this transect all imaged craters exhibiting diameters >7km were inspected for mounds.

130 The depth-diameter data for the craters in the region are derived as follows. Intact crater  
131 rims are digitised in MOLA data using the watershed methods detailed in Conway et al. (2012)  
132 and from this the centre-points calculated. The crater depths are taken as the lowest point on  
133 crater floor to the highest point on the rim according to gridded MOLA data and the diameters  
134 are estimated by calculating the average centre-to-rim distance (for more detail see Conway et al.  
135 2012).

136 Within each of the mound-bearing craters, all of the mounds are mapped. Where  
137 topographic data of the craters were available, the crater-floor mounds are identified as discrete  
138 rises from the crater floor, noted by a distinct break in slope. In the absence of topographic data  
139 the shadows cast by the mounds are relied on for identification; thus, the estimate for these  
140 craters is conservative. Mound-distribution density is calculated by means of four steps. 1.  
141 identifying the location of the mound(s) furthest from the crater-floor centre; 2. measuring the  
142 radius between the two points; 3. using this radial distance and, derivatively, circumference to  
143 calculate floor-surface area (km<sup>2</sup>); and, 4. dividing the surface area by the number of mounds  
144 located therein. Mound heights for two of the studied craters are measured using elevation data  
145 derived from HiRISE stereo-pairs (ESP\_017525\_2475, ESP\_017090\_2475 and  
146 ESP\_018210\_2445, ESP\_018078\_2445) using the methods described by Kirk et al. (2008) at the

147 NASA RPIF3D facility at UCL. Using the method of Okubo (2010), we estimate the vertical  
148 precision of these two DEMs to be 0.23m and 0.18m respectively. Only mounds that are not  
149 clustered tightly with others are used for height measurements so as to obtain a reliable base-  
150 height. Heights are taken as the difference between highest and lowest elevation value within the  
151 polygon delimiting the mound. Our discussion integrates the spatial location of craters  
152 containing paleo-lakes as presented in Table 1 of El Maarry et al. (2010). The set of craters  
153 analyzed in this investigation is a subset of the population discussed in their recent study.

### 154 *3. Mound morphology, traits and spatially associated crater-floor features in northern Utopia* 155 *Planitia*

156 Pingo-like mounds are ubiquitous on Mars, albeit mainly at mid or equatorial latitudes  
157 (Dundas et al., 2010), and have been discussed by a multiplicity of workers: i.e. Acidalia Planitia  
158 (Lucchitta, 1981); the Athabasca Valles and the Cerberus Plains (Burr et al., 2005; Page and  
159 Murray, 2006; Page, 2007; Balme and Gallagher, 2009), Maja Valles (Theilig and Greeley,  
160 1979); and mid Utopia Planitia (Dundas et al., 2008; Burr et al., 2009; de Pablo and Komatsu,  
161 2009; Lefort et al., 2009; Dundas and McEwen, 2010). By contrast, the putative CSPs observed  
162 by us occur uniquely at near-polar latitudes in the northern hemisphere ( 64-69°N) (**Fig. 3**).

163 Through the past few years Bruno et al. (2006), Dundas et al. (2008, 2010) and Burr et al.  
164 (2009a, b) have urged caution in the reporting of pingo-like mounds and suggested that much  
165 work remains before pingo hypotheses are validated. In particular, Dundas et al. (2010) points to  
166 the apparent contradiction between a late-Amazonian Epoch that is thought to be highly arid and  
167 the water volume requirements of pingo hypotheses. We address some of their concerns below  
168 (cf. section 4.3.2).

169 In our study region (a circum-global transect comprising 55-70°N), the floors or basins  
170 of five impact-craters show spatially-associated complexes of small-sized unsorted polygons and  
171 mounds whose size, shape, key geological characteristics and distribution are consistent with  
172 thermokarst-lake or alas/CSP assemblages such as those located in the TC (**Fig. 3**). Table 1  
173 presents the images used for each of these craters in the following analyses.

174 Host crater-diameters range from 7-19km (**Table 2**) and none of their ejecta deposits  
175 exhibit inward-oriented breaches or flow features. Sixty-seven other craters at or above the  
176 minimum crater diameter of 7km were imaged by the MOC and HiRISE cameras but did not  
177 show spatially-associated complexes of polygons and mounds. Host crater-depths are shallow  
178 compared with global crater depth-diameter estimates (Garvin et al., 2003)(**Fig. 4, Table 2**).  
179 However, this is consistent with the measurements of crater depths in the 10-25km diameter  
180 range above 52°N made by Kreslavsky and Head (2006). Intriguingly, each of the polygon and  
181 mound-bearing craters occur in northern UP within a tight latitudinal band (~64-69°N) and a  
182 narrow longitudinal reach (~26-98°E). This could be indicative of surface and/or atmospheric  
183 boundary conditions that are highly localised and possibly consistent with landscape  
184 modification by periglacial processes.

185 Mound diameters range from tens to hundreds of metres (**Figs. 5 and 6, Table 2**); mound  
186 heights extend from ~6-33m (**Table 2, Fig. 5**). In cross-section, the mounds are conical to  
187 domical in shape and have low flank-slopes of up to ~15° (**Fig. 5**). We do not observe summit  
188 fractures as seen in many pingos in TC but occasionally circular raised-rims with basal diameters  
189 similar to those of the crater-floor mounds are observed in proximity to these mounds (**Fig. 6**).  
190 These could be mound remnants or slump markers. Mound shape in plan view is circular to  
191 elongate (**Figs. 5 and 6**); mound distribution is clustered around or at the crater-floor centres.

192 Mound density in **Fig. 5** is  $\sim 0.9$  mounds/km<sup>2</sup> and 0.4 mounds/km<sup>2</sup> in **Fig. 6** (also, cf.  
193 supplementary **Figure 1**). Some mounds are nested directly on the crater floor; others, seem to  
194 lie atop ridge-like structures that show a ring-like appearance (**Fig. 6**).

195 All of the mound-bearing craters display floors dominated by unsorted polygonal-  
196 patterned ground  $\leq \sim 350$ m in diameter (**Fig. 6**). Polygonisation is typical of the terrain within and  
197 around impact craters at this latitude (Gallagher et al., 2011). Some of crater-floor polygons  
198 cross-cut the mounds (**Fig. 5C**); others show an orthogonal orientation (**Fig. 6**). Recent estimates  
199 of crater-retention ages at this latitude, using the Heimdal Crater (68.3°N; 235.2°E) as a  
200 benchmark, suggest that the polygonised terrain is within the 0.5-2.0 Ma range (Gallagher et  
201 al., 2011).

#### 202 **4. Discussion - Mound Origins**

203 Here we consider three mound-formation hypotheses in the light of our new observations  
204 as well as the recent work of Conway et al. (2012) and El Maarry et al. (2010, 2012).

##### 205 **4.1 Weathered uplift-complexes**

206 On Mars, small ( $< 5$ km) impact craters are noted for having a relatively simple, bowl-  
207 shaped geometry (Werner et al., 2004; Wood et al., 1978). Large craters, particularly those above  
208 the  $\sim 8$ -10km range of diameter, exhibit complex morphologies that include terraced walls and  
209 regions of central uplift (Garvin et al., 2003; Wood and Andersson, 1978). Central uplift occurs  
210 in the modification and collapse phase of crater formation, following the formation of a transient  
211 cavity, as weak material collapses and returns to a state of gravitational equilibrium (Bond, 1981;  
212 Melosh, 1989). Regions of central uplift are typically domical, have one or several peaks, and  
213 exhibit maximum heights that are well below crater-rim crests and the level of surrounding  
214 plains (Bond, 1981).

215           There are two general observations suggesting that the observed mounds are weathered  
216 and/or partially-buried remnants of central-uplift material: 1. the mounds are clustered in the  
217 central region of the crater floors; and, 2. the craters in which they lie are above the threshold  
218 diameter for central-uplift formation. Under this scenario the central-uplift structures or  
219 complexes would have gradually undergone burial by sedimentation; once the crater-fill was  
220 sufficiently thick only the uplift summits would be visible, somewhat like nunataks in the  
221 Antarctic (**Fig. 7**). Weathering and erosion could have carved these structures into mounds  
222 similar in appearance to the ones observed on the crater-floors of UP. This scenario is consistent  
223 with the fact that craters serve as traps for dust and regolith over time and that our studied craters  
224 are observed to have relatively shallow depths (**Fig. 4**). Some authors have suggested that high-  
225 northern craters might be filled with dusty-ice (e.g. Kreslavsky and Head, 2006) and/or  
226 sediments deposited during the presence of a northern ocean (e.g. Boyce et al., 2005).

227           The plausibility of the central-uplift hypothesis is contingent upon crater-fill levels lying  
228 below the upper elevation-threshold of impact-related crater-floor structures. Even though  
229 accurate *in situ* measurements of fill depths are not available, estimates of fill depth can be  
230 calculated by using 1. MOLA profiles to identify crater diameters and rim elevations; and, 2.  
231 generally-accepted assumptions concerning the depth-to-diameter dimensions of complex  
232 craters. The latter comprise the following:

233           (a) Crater diameter is stable over time, changing by no more than 10-15% from its initial  
234 value as craters degrade (Craddock and Maxwell, 1990).

235           (b) Crater depth is diameter dependent and relatively accurate predictions of initial crater  
236 depth can be made from generalized formulae (Boyce et al., 2005; Garvin et al., 2003;  
237 Stewart and Valiant 2006).

238 (c) The height of central-uplift structures is diameter dependent and is well below the  
239 level of the surrounding plains (Garvin et al., 2003; Werner et al., 2004).

240 Using these assumptions we have identified five key characteristics of the five principal  
241 mound-bearing craters and summarise them here; more detail is available in Table 2: 1. rim-to-  
242 floor/top of fill depth (actual); 2. initial depth (estimated); 3. initial depth (estimated) to current  
243 floor (actual); 4. central-peak height (estimated); and, 5. height difference (estimated) between  
244 the current floor (actual) and the central-peak summit (estimated). Each of the mound-bearing  
245 craters show a minimum height difference of ~600m between the fill/crater floor level and the  
246 buried summit of the crater's central peak (**Table 2**). This difference of height is exemplified by  
247 comparing a MOLA profile that crosses the crater floor and central peak of a non mound-bearing  
248 complex crater in the northern plains (**Fig. 8a**) with a MOLA profile that crosses one of the five  
249 mound-bearing craters in the region (**Fig. 8b**).

250 As the crater-floor mounds and spatially-associated ridges occur well above the heights  
251 predicted for central peaks in each of the mound-bearing craters, this suggests that the mounds  
252 and ridges could not be partially-exposed central peaks or peak remnants. Interestingly, Stewart  
253 and Valiant (2006) suggest that Garvin's formulae underestimate the initial depth of complex  
254 impact-craters in some areas of the northern plains.

255 Are the initial depths of impact craters in the high northern plains shallower than  
256 elsewhere on Mars? Based on the following observations this seems unlikely: 1. the  
257 morphological traits associated with the high-northern craters, such as ejecta smoothing, are  
258 consistent with them having experienced high levels of infilling and modification (Garvin et al.,  
259 2003; Kreslavsky and Head, 2006); 2. there are some relatively pristine craters (distinguished by  
260 rough and easily visible ejecta-blankets) in this region that have depths exceeding the predicted

261 initial depth for craters with specific diameters derived of global averages (Garvin et al.,  
262 2003)(**Fig. 4**); and, 3. although variation in the lithology of impact targets has an influence on  
263 initial crater geometry (e.g., as summarized in Stewart and Valiant, 2006), significant infilling is  
264 still implied by the shallow depths observed in the mound-bearing craters compared to other  
265 craters in the surrounding area (**Fig. 4**).

266 Finally, if we consider that the craters in our study are outliers to the general population  
267 and therefore anomalously shallow then does the small-scale morphology of the mounds make  
268 sense as central complex remnants? Without a concrete example of a deeply buried central-uplift  
269 elsewhere on Mars we cannot compare directly the dimensions and density of mounds that we  
270 observe in UP. However, for craters 2 and 5 in particular it seems unlikely that a central-uplift  
271 complex could possess so many and such widely distributed (from the crater centre to within  
272 ~2km of the crater rim) peaks of almost the same height.

273 In summary, it is unlikely that these mounds are remnants of central uplift complexes,  
274 because the implied level of fill surpasses estimated uplift-elevations by over 600m (**Table 2**);  
275 moreover, in some cases the mound morphology is not consistent with the expected morphology  
276 of buried central-uplift complexes.

#### 277 ***4.2 Impact-related hydrothermal structures***

278 Impact-related hydrothermal activity (Newsom, 1980) could be the progenitor of the  
279 crater-floor mounds. For example, amongst the geological traits observed at the Hesperian-aged  
280 Toro impact crater on the northern edge of the Syrtis Major Volcanic Plains (17.0°E; 289.2°N)  
281 are mounds, polygonal fractures, veins and structural discontinuities that could be the result of  
282 volatile release and/or liquid flows (Fairen et al., 2010; Marzo et al., 2010). Distinctive  
283 mineralogy and abundances of hydrated phases in and around the central-uplift complex, perhaps

284 associated with impact-melt bearing crater-fill deposits, also are consistent with a hydrothermal  
285 origin of these structures (Marzo et al., 2010). The mounds and polygonal cracks observed here  
286 have similar dimensions to those that we observe in UP (**Fig. 9**); however, the close spatial-  
287 association of the mounds and polygons is not observed.

288 By a similar argument to that which is made for the central-uplift remnant hypothesis, the  
289 hydrothermal hypothesis can also be rejected. Although some of the crater fill in the mound-  
290 bearing craters could be associated with the impact formation of the craters themselves, the fill  
291 height of these craters exceeds the hypothesised level of impact-related melt material as well as  
292 central peak summits. For example, Toro crater is ~40km in diameter, has a rim to floor depth of  
293 ~2km and the central-peak summit rises 400m above the current crater floor (Marzo et al.,  
294 2010). By fitting a planar surface through the MOLA data exterior to this crater's ejecta; we  
295 were able to estimate the elevation difference between the plains and the central peak as ~960m.  
296 This means that the elevation of the central-uplift structure and, derivatively, the impact-related  
297 fill deposits, lie well below the elevation datum of the surrounding plains. In addition, although  
298 the mounds in Toro are located near the centre of the crater they are not atop the central uplift;  
299 this is where you would expect them to be located if they were exposed sub-aerially subsequent  
300 to the infilling of the host crater. By contrast, the putative CSPs in northern UP lie atop hundreds  
301 of metres of fill, almost at the elevation datum of the surrounding plains (Soare et al., 2011b).

### 302 ***4.3 Perennial ice-cored mounds (pingos)***

#### 303 ***4.3.1 Thermokarst lakes on Earth and the possible origin of closed-system pingos***

304 In periglacial landscapes such as the TC, closed-system pingos form where thermokarst  
305 lakes either have lost or are in the process of losing their water by drainage or evaporation  
306 (Mackay, 1998) (**Fig. 1**). Exposure of the previously unfrozen lake-floor to freezing temperatures



307 leads to permafrost aggradation downwardly through the lake-floor sediments and inwardly from  
308 the lake margin (Mackay, 1998). As the permafrost aggrades, pore water is placed under  
309 increasing hydrostatic pressure and migrates away from the freezing fronts. Impelled by this  
310 pressure, the pore water uplifts and deforms the newly frozen lake-floor; this happens at or near  
311 the centre of the lake-floor where the permafrost is particularly thin and where small residual  
312 ponds may occur (Mackay, 1998). When the pore water (injection ice) freezes beneath the  
313 uplifted lake floor an ice-core forms, providing the buttress of a perennial sediment-covered  
314 mound or pingo (Washburn, 1973, Mackay, 1998; French, 2007)

315 Polygonal-patterned ground formed by thermal-contraction cracking often surrounds and  
316 cross-cuts the pingos (**Fig. 2b**); ice wedges, the product of seasonal thaw, underlie polygon  
317 margins or troughs. In some instances, the polygons may show an orthogonal orientation (Soare  
318 et al., 2008, 2011a); this is a marker of the episodic loss of water in a thermokarst lake  
319 (Lachenbruch, 1962). When their ice-cores degrade and the mounds undergo ablation, slump  
320 material forms a raised-rim mound remnant (**Fig. 2c**) (Mackay, 1998; Washburn, 1973).

321 The Martian crater-floor mounds approximate terrestrial CSPs (of the TC type) in shape,  
322 size and spatial association with small-sized polygonal patterned-ground. In a survey of 1247  
323 pingos (of which 98% are estimated to be hydrostatic) in Arctic Coastal Plain, northern Alaska,  
324 Jones et al. (2012) find that pingo heights range from 2 to 21m (mean 4.6m), diameter 32 to  
325 295m (mean 94m) and maximum density of 0.18 per km<sup>2</sup>. A similar study of 3109 mostly  
326 hydrostatic pingos in northern Asia (Grosse and Jones, 2011) found that pingo heights range  
327 from 2-37m (mean 4.8m), and have a maximum density of 0.28 per km<sup>2</sup>. Hence, the UP  
328 mounds are slightly larger on average compared to pingo populations on Earth but they do have a  
329 similar height-to-diameter ratio. The density of the UP pingos is slightly higher than that

330 reported in the Jones et al. (2012) and Grosse and Jones (2011) studies; however if we consider a  
331 single basin in TC, we obtain a density of 3 per km<sup>2</sup>, hence the measurement of the density of  
332 pingos is susceptible to the scale considered. Pingos undergoing degradation on Earth often  
333 possess summit cracks, but we do not observe this in UP. The absence of summit cracks on the  
334 mounds in UP does not rule them out as being pingos, as many pingos on Earth never reach the  
335 threshold of size and stress for this to occur.

336 Of the three hypotheses presented and discussed above, the periglacial or closed-pingo  
337 system hypothesis also is the only one that is stratigraphically consistent with the depth  
338 calculations (initial and actual) of the mound-bearing complex craters in northern UP. That is to  
339 say, if the pingo-like mounds comprise post-fill structures or structures associated with a post-fill  
340 revision of the near-surface regolith, then their occurrence atop the fill would be expected.

#### 341 *4.3.2 Late Amazonian crater-lakes and climatic water-ice accumulation*

342 In their recent work Conway et al. (2012) have documented eighteen (km-scale) impact  
343 craters at latitudes  $\geq 70^\circ\text{N}$  that host large (mostly km-scale) perennial domes. Spectral data  
344 acquired by the MEX OMEGA (Mars Express, Observatoire pour la Minéralogie, l'Eau, les  
345 Glaces et l'Activité) show high water-ice concentrations (up to 0.7 band depth) at the surface of  
346 some of these craters (Conway et al., 2012). None of the host craters are smaller than 9.5 km in  
347 diameter; ten craters exhibit diameters from 9.5-20km. The maximum thickness of their water-  
348 ice domes ranges from 94-1640m and the ice mound-summit-to-rim distance varies from 13-  
349 626m. Interestingly, each of the impact craters that show pingo-like mounds on their floors have  
350 diameters between 7.3-18.8 km (cf. Table 2).

351 Conway et al. (2012) hypothesise that these massive ice-domes form from water-ice  
352 vapour transported from the north-polar region and cold-trapped in their host craters (**Fig. 10**).

353 Cold-trapping could be triggered by the higher atmospheric pressure and lower temperature of  
354 crater interiors; in turn, this would increase the accumulation rates of water-ice during the winter.  
355 Were accumulation significant enough then this water-ice could be preserved through the spring  
356 and summer when the seasonal polar cap retreats, creating a perennial ice-dome. Once formed,  
357 the ice domes comprise a positive feedback-loop whereby their high albedo and high thermal-  
358 inertia but low temperatures are a permanent cold trap for condensation.

359 Similar domes could have evolved in the craters where the putative CSPs occur, under  
360 orbital parameters where the stability zone of ice-dome formation extends slightly further to the  
361 south than is the case currently (  $64^{\circ}\text{N}$ , according to the southern-most crater where the CSPs  
362 are located). This is likely to be a period with higher obliquity and/or eccentricity that lengthens  
363 the northern-winter. When Mars returns to antecedent orbital-parameters the stability zone of  
364 ice-dome formation in the northern hemisphere would migrate polewardly; depending upon  
365 regional boundary conditions the more southerly domes either would sublimate or thaw, pool and  
366 form endogenic paleo-lakes.

367 Indirect evidence of paleo-lakes having formed at the latitudes of the current ice-domes  
368 and the putative CSPs has been reported by El Maarry et al. (2008, 2010). They have studied the  
369 fracture mechanics of crater-floor polygons at near-polar latitudes in the northern hemisphere of  
370 Mars. The polygons range in diameter from  $\sim 15\text{-}350\text{m}$  and are located principally between  $65\text{-}$   
371  $75^{\circ}\text{N}$  (El Maarry et al., 2010)(**Fig. 3**). El Maarry et al. (2010) hypothesise that under present  
372 boundary conditions the crater-floor polygons with diameters  $\geq 75\text{m}$  can be formed only by  
373 desiccation, not by sublimation-related processes; if so, then this points to the antecedent  
374 occurrence of paleolakes in the host crater-basins (El Maarry et al., 2010). With regard to the  
375 crater-floor polygons  $\leq 75\text{ m}$ , their formation could be the result of desiccation (El Maarry et al.,

376 2010) or thermal contraction (El Maarry et al., 2010; also, Soare et al., 2005). Polygon formation  
377 by means of thermal-contraction cracking, particularly when the polygons exhibit an orthogonal  
378 orientation as some of them do in the putative CSP craters, also points to periglacial processes at  
379 work in a lacustrine environment (Lachenbruch, 1962).

380 Two other landscape characteristics are consistent with the antecedent occurrence of  
381 paleolakes in the CSP impact craters: ridge-like structures on the crater floors and the relative  
382 location of the CSPs themselves. With regard to the former, these might be sedimentary markers  
383 or paleo-shorelines of a lake in recession or of residual ponds forming prior to the complete loss  
384 of lake water on the crater floor. On the other hand these ridges could be indicative of a  
385 structural control on the migration of subsurface volatiles, as there is often a genetic/spatial  
386 linkage among tectonic (e.g., faults and joints), and emplaced (e.g., dikes and elongated plugs,  
387 hydrothermal mounds, migrating pingos) landforms (Dohm, 1995, Dohm et al., 2001; Tanaka et  
388 al., 1998; Wu et al., 2005).

389 With regard to the latter, and as noted above, the formation of CSPs on Earth tends to  
390 occur at or near the centre of a host thermokarst lake, this being the site of thin permafrost where  
391 remnant water pools last (Mackay, 1998). The putative Martian CSPs show clustering at or near  
392 the centre of their host craters that is consistent with terrestrial thermokarst-lake/CSPs  
393 assemblages (Fig. 1g).

394 A possible constraint on the CSP hypothesis concerns the availability of liquid water  
395 volumetrically sufficient to generate CSPs on crater floors at high northern latitudes (Dundas et  
396 al., 2010). However, the current thicknesses and summit-to-rim distances of ice domes in craters  
397 comparable in diameter to those hosting pingo-like mounds suggest that the water requirements  
398 of the latter can be met were pre-cursor ice-domes to have formed in the mound-bearing craters.

399 As noted above, ice dome thicknesses in craters with diameters of 9.5-20km ranges from tens to  
400 hundreds of metres and summit-to-rim distances comprise hundreds to thousands of metres in  
401 reach (Conway et al., 2012).

402 Using a DEM we have calculated the heights of two putative CSPs (15m, cf. Table 2).  
403 Even if one assumes a volumetric loss of 9% when water ice changes phase to liquid water as an  
404 ice domes thaws and melt-water pools on a crater floor, ice-dome thickness largely exceeds the  
405 height of the pingo-like mounds by an order of magnitude. In some instances, summit-to-rim  
406 distances also exceed mound diameters by an order of magnitude.

#### 407 ***Conclusion***

408 Compared to the alternative hypotheses, the periglacial hypothesis is much more robust  
409 and coherent in explaining crater-floor mound formation in northern UP. It integrates  
410 geomorphological, stratigraphical and climatological observations, assumptions and estimates  
411 whereas the alternatives do not. Moreover, only the periglacial hypothesis is consistent with fill-  
412 depth estimates of the mound-bearing impact craters.

413 In terms of shape, size key geological characteristics and distribution, the crater-floor  
414 mounds of northern UP are consistent with the shape, size, key geological characteristics and  
415 distribution of CSPs in terrestrial periglacial-environments such as the Tuktoyaktuk Coastlands.  
416 Moreover, regardless of whether the small-sized polygons located in craters with pingo-like  
417 mounds are the result of desiccation or thermal contraction, both processes are associated with  
418 lake evolution on Earth and are consistent with the CSP hypothesis.

419 We suggest that the landscape assemblage comprised of crater-floor pingo-like mounds  
420 and small-sized polygons is a paleo-marker of freeze-thaw cycling and of a surface /near-surface  
421 system, albeit a highly localised one, rich in water. Consequently, the atmospheric boundary

422 conditions of temperature, atmospheric pressure and humidity required to initiate and maintain  
423 the freeze-thaw cycling of water would have been much higher than many workers have thought  
424 possible in the region during the late Amazonian Epoch.

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## 558 **Figures**

- 559 **1.** The Pingo Canadian Landmark is a national park 6km southwest of Tuktoyaktuk adjacent  
560 to the Beaufort Sea in the Tuktoyaktuk Coastlands of northern Canada. Image (A27917-35-  
561 1993) courtesy of the Canadian Air Photo Library. Amongst the numerous pingos located  
562 here are Ibyuk (circular and ~49m in height) at the right; Split (sub-circular and ~ 35m in  
563 height) at the centre; and, an un-named elongated pingo at the top of the image on the left.
- 564 **2. a-e)** An idealised schema of closed-system pingo evolution in the Tuktoyaktuk Coastlands  
565 (TC) of northern Canada (Mackay, 1998). This is discussed in detail in Section 4.3.1. **f)** A  
566 small thermokarst lake surrounded by thermal-contraction polygons (TC, early July 2007).  
567 Image credit: R. Soare. **g)** A three-pingo complex in the midst of a thermokarst lake losing its  
568 water by evaporation and/or drainage. Note the un-vegetated and pale margins of the lake  
569 and pingos, indicative of water loss that is relatively recent (TC, early July 2007). Image  
570 credit: R. Soare. **h)** The end-stage of pingo evolution is a raised-rim landform or scar  
571 comprised of slump material, as exemplified by this oblique view of a collapsed pingo in the  
572 Brooks Mountains of Alaska (Hamilton and Obi, 1982).
- 573 **3.** Map showing the spatial distribution of mound-bearing impact craters in northern Utopia  
574 Planitia: the map incorporates a MOLA hillshade-background image (courtesy of  
575 [www.jpl.nasa.gov](http://www.jpl.nasa.gov)) and the following CTX images comprise the crater mosaic below the  
576 map: B02\_010392\_2491, P16\_007372\_2474, B22\_018078\_2445, P19\_008492\_2446,  
577 B19\_017089\_2341 and B19\_017154\_2472 (courtesy of MSSS/Caltech/JPL).

- 578 **4.** Depth-diameter plot of the craters in the region local to those containing mounds, i.e. 62-  
579 70°N and 26-98°E, as mapped by Conway et al. (2012). The craters with mounds and the  
580 craters mapped as containing evidence of crater lakes by El Maarry, et al. (2010) are  
581 highlighted. The depth-diameter relationship found by Garvin et al. (2003) is included as a  
582 reference.
- 583 **5.** Mounds on the floor of crater # 2, HiRISE image ESP\_017090\_2475 (courtesy of  
584 NASA/JPL/U of A) overlain on CTX image P16\_007372\_2474 (courtesy of  
585 MSSS/Caltech/JPL). 10m contours are derived from a 1m/pixel DEM produced from HiRISE  
586 images ESP\_017525\_2475, ESP\_017090\_2475. Online version has a color-drape which was  
587 derived from the HiRISE DEM. Stars indicate the locations of the mapped mounds used to  
588 produce the statistics in Table 2. Cross-sections whose locations are indicted on the image  
589 insets A-C are also derived from the same elevation data.
- 590 **6.** Mounds in crater # 3, HiRISE image PSP\_007780\_2450; 64.5°N, 63.7°E; 25 cm/pixel  
591 (courtesy of NASA/JPL/U of A). Note the diversity of mound morphology, highlighted in the  
592 white boxes: i) circular, ii) elongate and iii) remnant, possibly a mound scar. Clustering at or  
593 near the crater-floor centre is a keynote of mound distribution, as is a ring-like appearance.
- 594 **7.** Central peak of well-preserved crater northwest of Tartarus Montes: HiRISE  
595 PSP\_009240\_2055; 25.0°N, 167.6°E; 25 cm/pixel (courtesy of NASA/JPL/U of A).
- 596 **8. a)** Plan and profile view of a ~13.5km diameter mound-bearing crater at 67.2°N, 47.8°E. The  
597 solid black line is derived from MOLA profile 20037 and presents the level of the crater floor  
598 to be very near that of the surrounding plains. The serrated black line shows an estimate for  
599 the initial depth of the crater based on a power law derived from Garvin et al. (2003). CTX  
600 image P16\_007372\_2474 was used for the top of the figure (courtesy of CalTech/JPL). **b)**

601 Plan and profile view of a ~18.7km diameter crater with a central peak at 38.6°N, 137.2°E.  
602 MOLA profile 12352 crosses the crater's central peak, indicating that it is well below the  
603 level of the surrounding plains. Crater image is cropped from THEMIS visible wavelength  
604 image V09919018 (courtesy of NASA/JPL/ASU).

605 **9.** Hydrothermal features on the floor of Toro crater (17.0°E; 289.2°N) in HiRISE image  
606 PSP\_005842\_1970 (courtesy of NASA/JPL/U of A). A) Small-scale mounds on the floor of  
607 Toro crater, marked by white arrows. B) Polygonal pattern on the floor of Toro crater.

608 **10.** Oblique view of the ice dome in Korolev crater (~80km diameter). View is from the rim at  
609 72.9°N, 162.6°E looking to the east. The elevation data used for this view are MOLA gridded  
610 data and the height of the dome from the trough is ~1 km. CTX images used:  
611 P21\_009042\_2528 and P20\_008831\_2529 (courtesy of MSSS/Caltech/JPL).

612

613 **Tables**

614 **Table 1.** Crater floors studied in this article, their locations and the images used. Crater IDs marked with \* indicate those craters  
 615 included in the Soare et al. (2005) study.

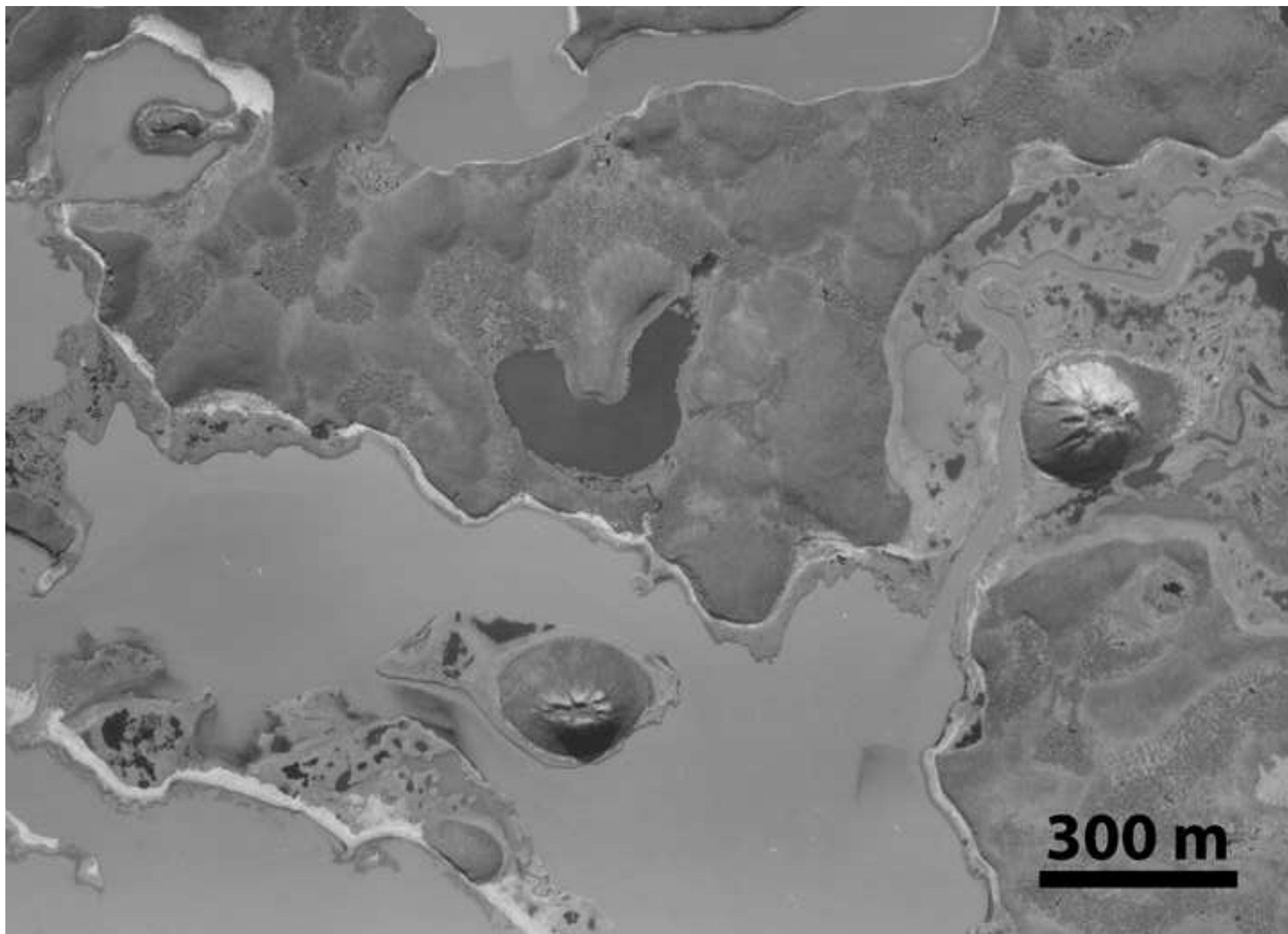
Crater ID	Latitude (°N)	Longitude (°E)	HiRISE images	MOC images	CTX images
1	68.945	26.760	PSP_008757_2490, ESP_017691_2910		B02_010392_2491
2	67.193	47.845	PSP_007372_2475, ESP_017525_2475, ESP_017090_2475		P16_007372_2474
3*	64.476	67.285	PSP_008492_2450, PSP_007780_2450	E0300299	P19_008492_2446
4*	64.324	70.378	ESP_015942_2445, ESP_018210_2445, ESP_018078_2445	E0500113	B22_018078_2445
5	67.131	97.547	ESP_017009_2475, ESP_017154_2475, ESP_017576_2475		B19_017154_2472

616

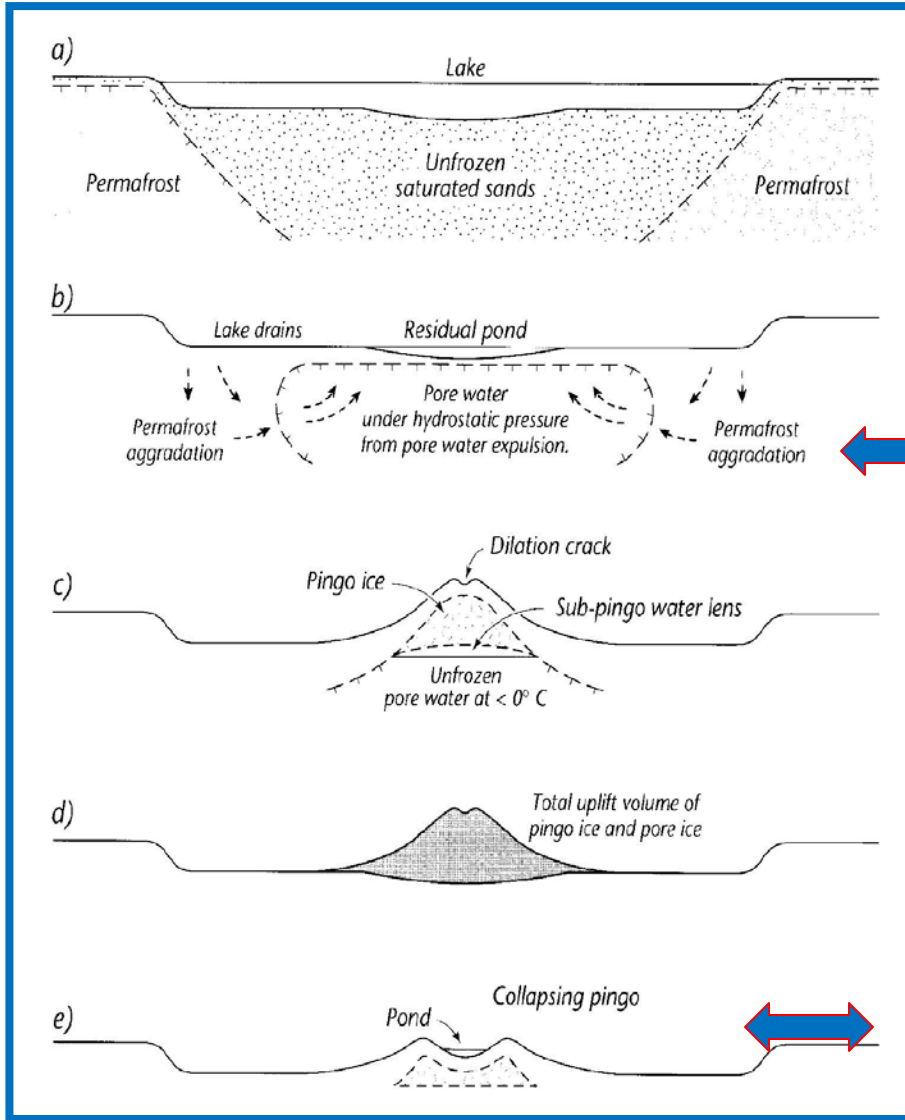
617 **Table 2.** Characteristics of craters containing mounds and the mounds themselves. Crater-elevation data are taken from MOLA and  
 618 mound-elevation data are taken from HiRISE stereo-elevation models (cf. supplementary Figure 1).

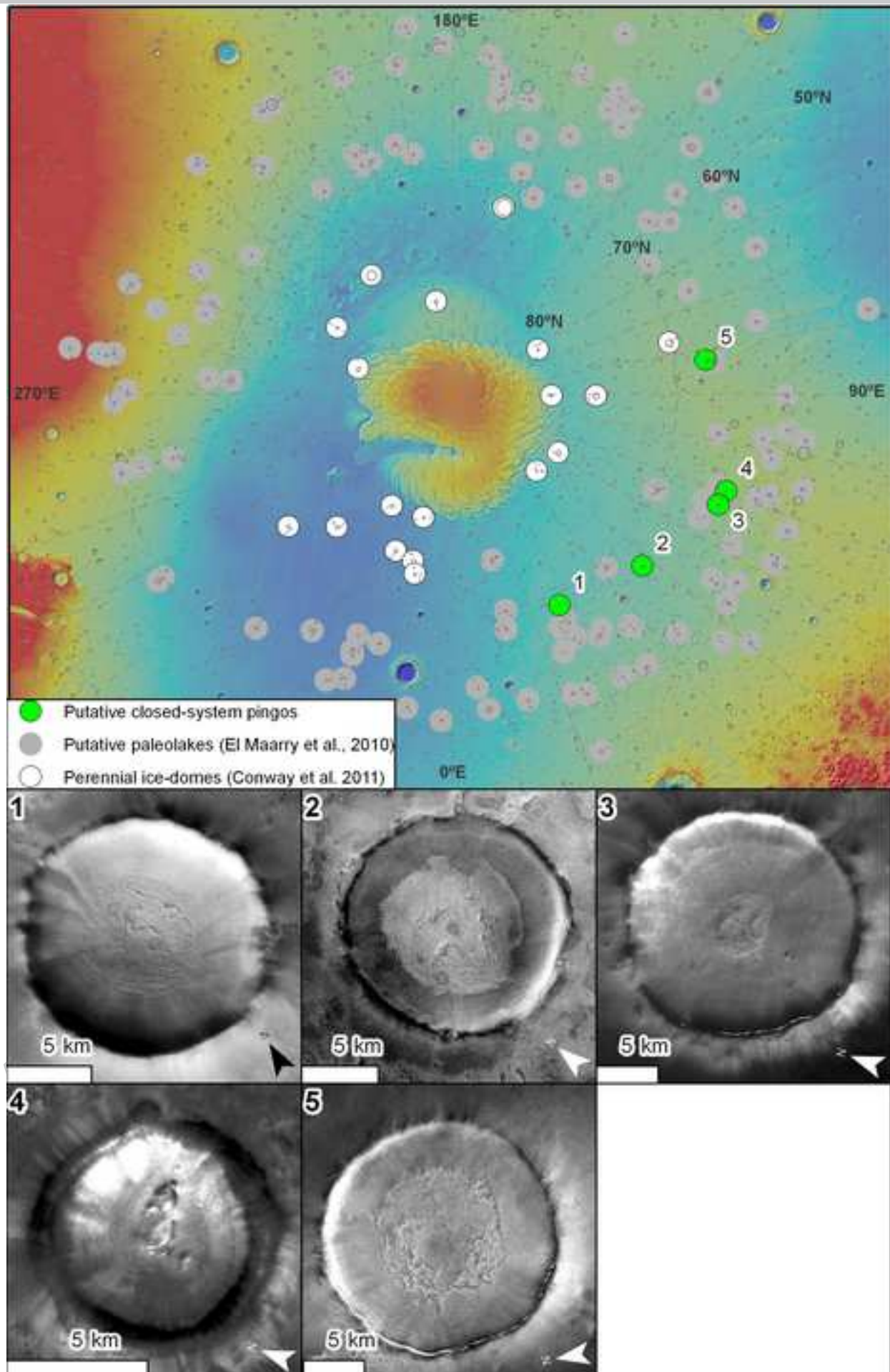
Crater ID	Depth (m)	Diameter (km)	Predicted depth from Garvin et al. (2003) (m)	Estimated fill thickness (m)	Central uplift height from Garvin et al. (2003) (m)	Estimated elevation difference - central uplift to surface (m)	# of mounds (# used for height measurements)	Aerial extent of mound-basin (km <sup>2</sup> )	Mound density (#/km <sup>2</sup> )	Mean height in metres (range)	Mean diameter in metres (range)
1	553	14.0	1312	759	154	605	13	30	0.43		
2	437	14.1	1316	879	154	725	44 (16)	51	0.86	15 (6-33)	278 (186-458)
3	518	18.2	1492	974	176	798	36	128	0.28		
4	218	7.3	954	736	110	625	8 (8)	12	0.67	15 (8-22)	194 (86-366)
5	446	18.8	1516	1070	179	891	68	105	0.65		

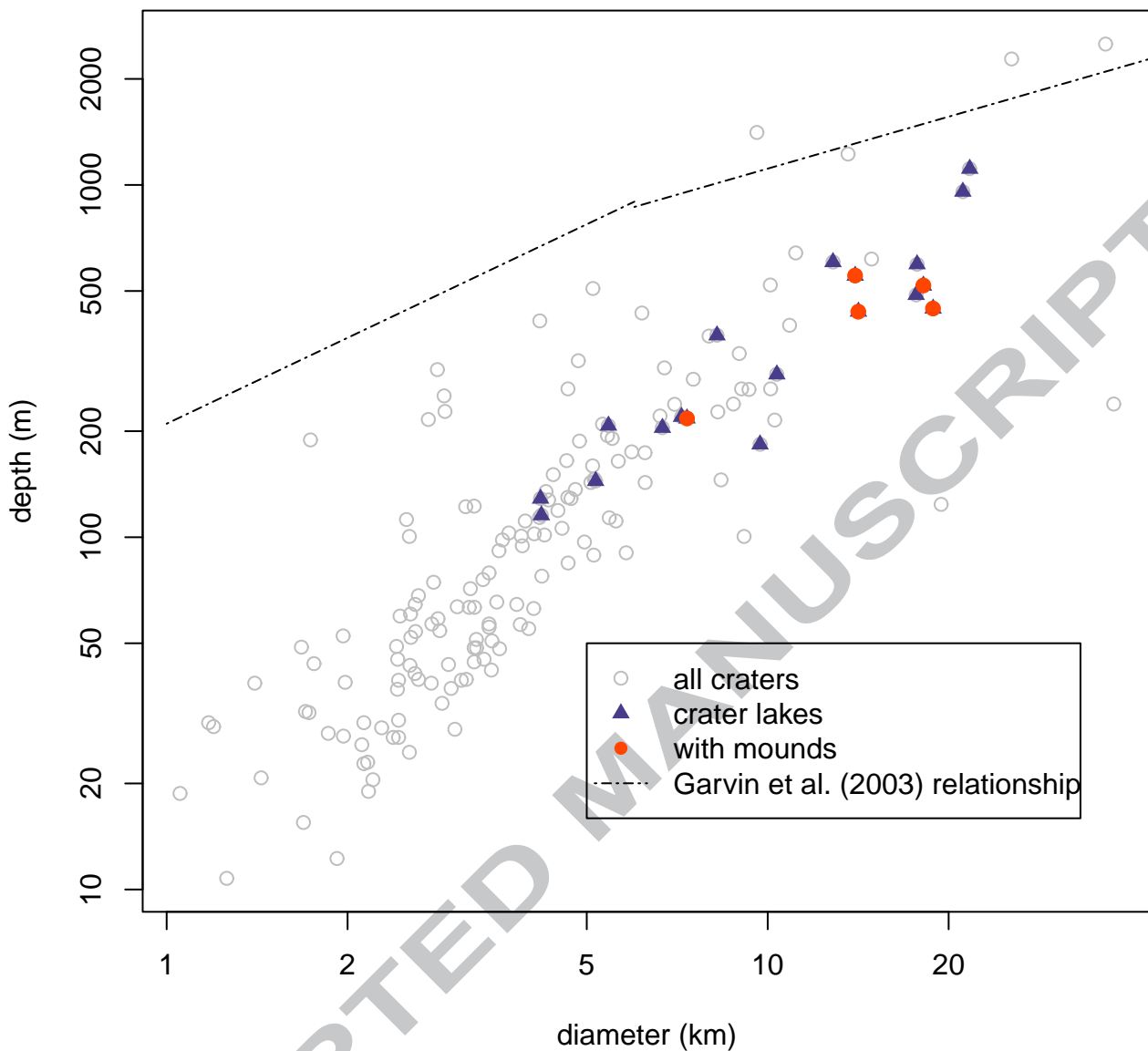
619

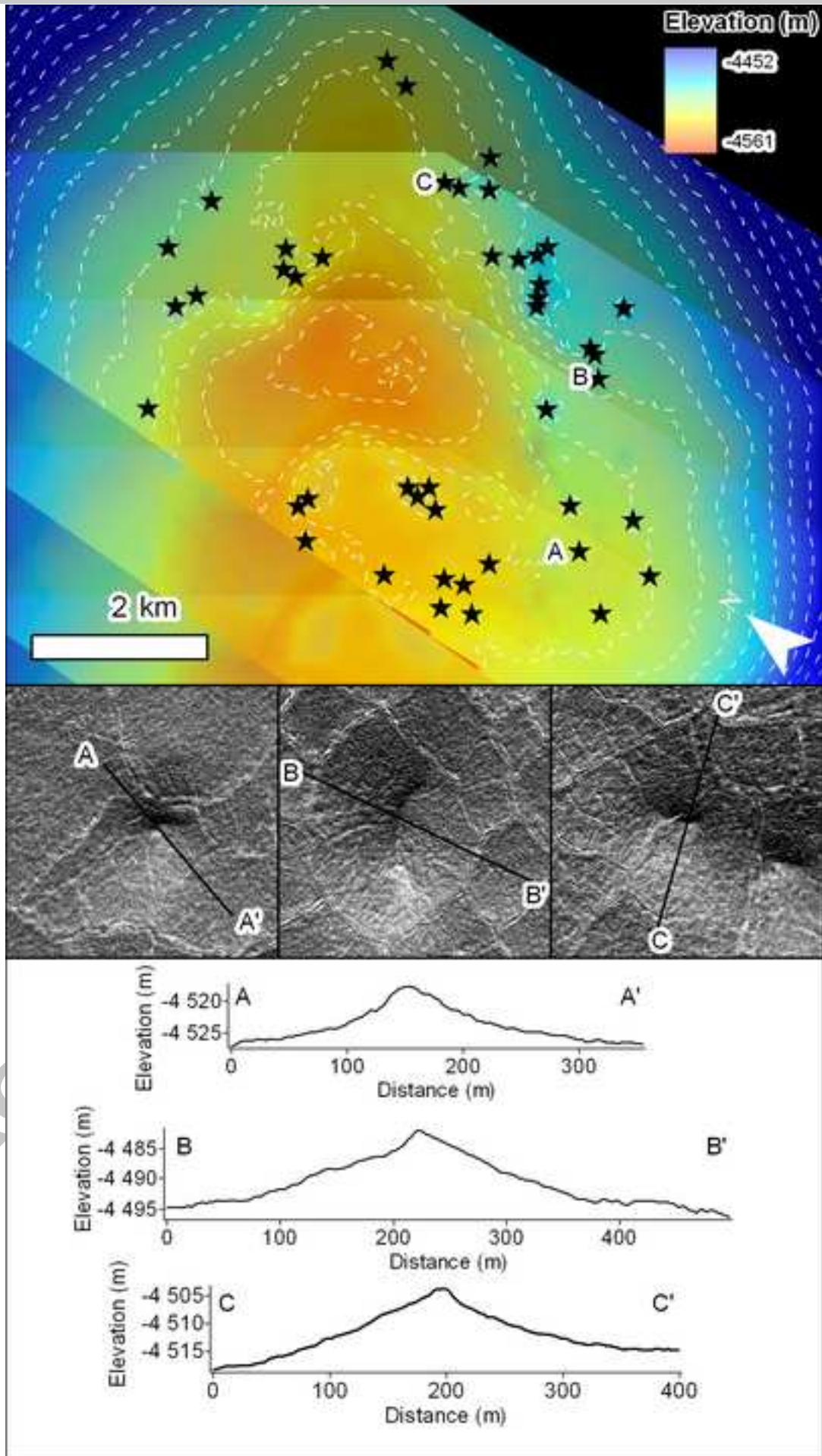


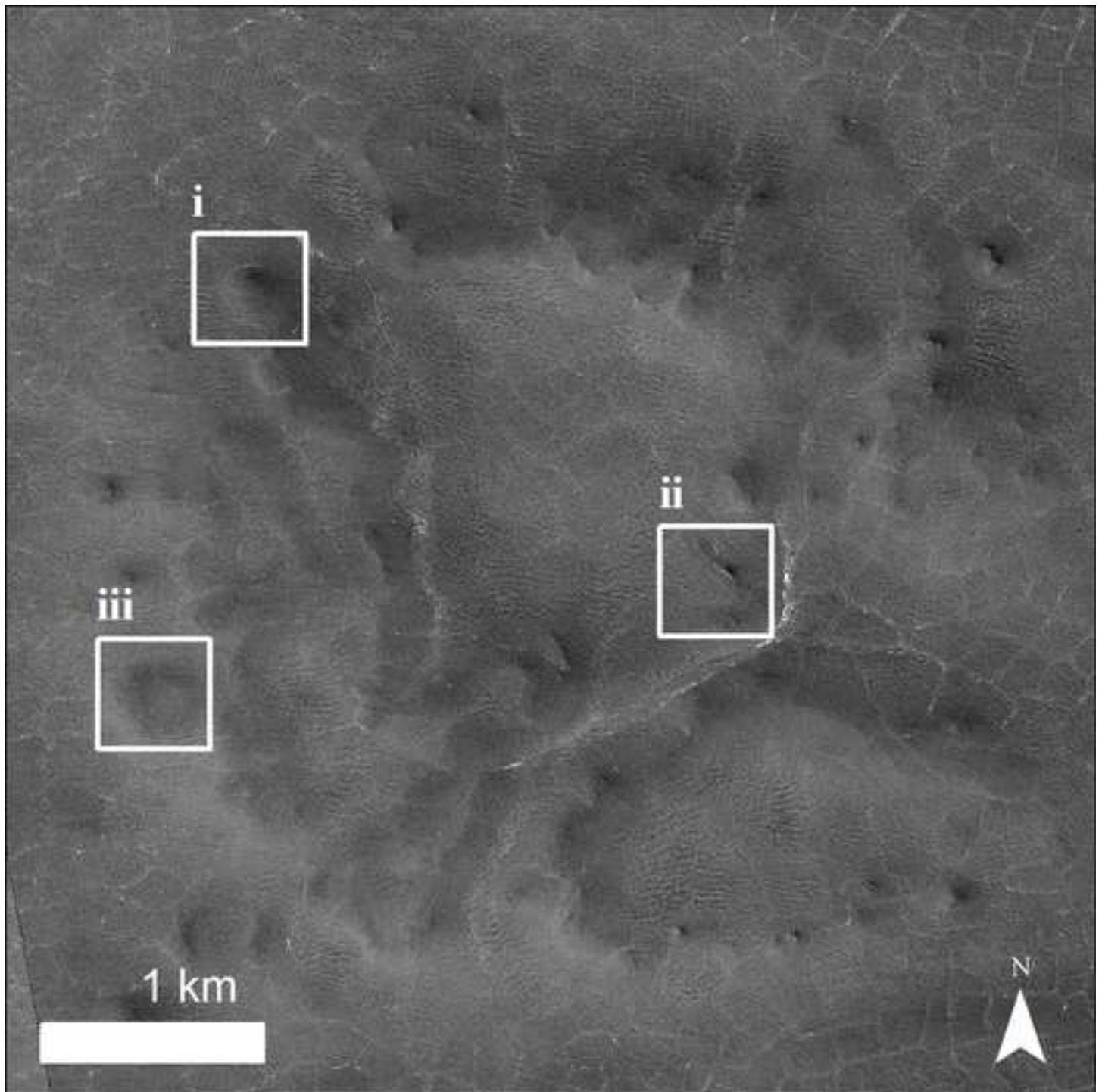


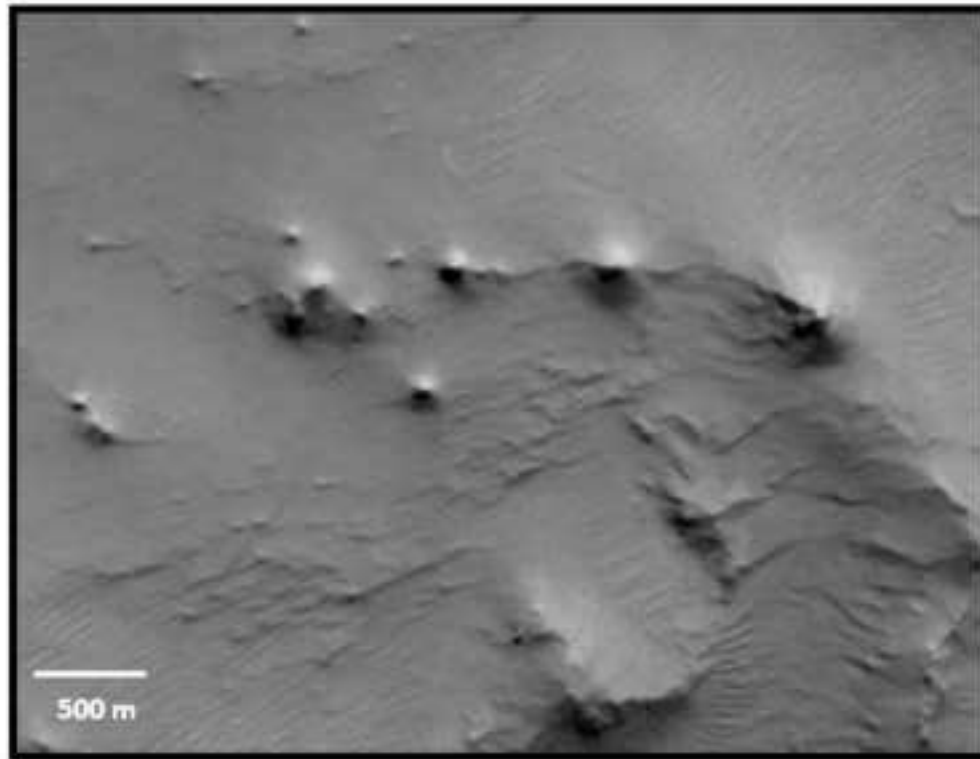


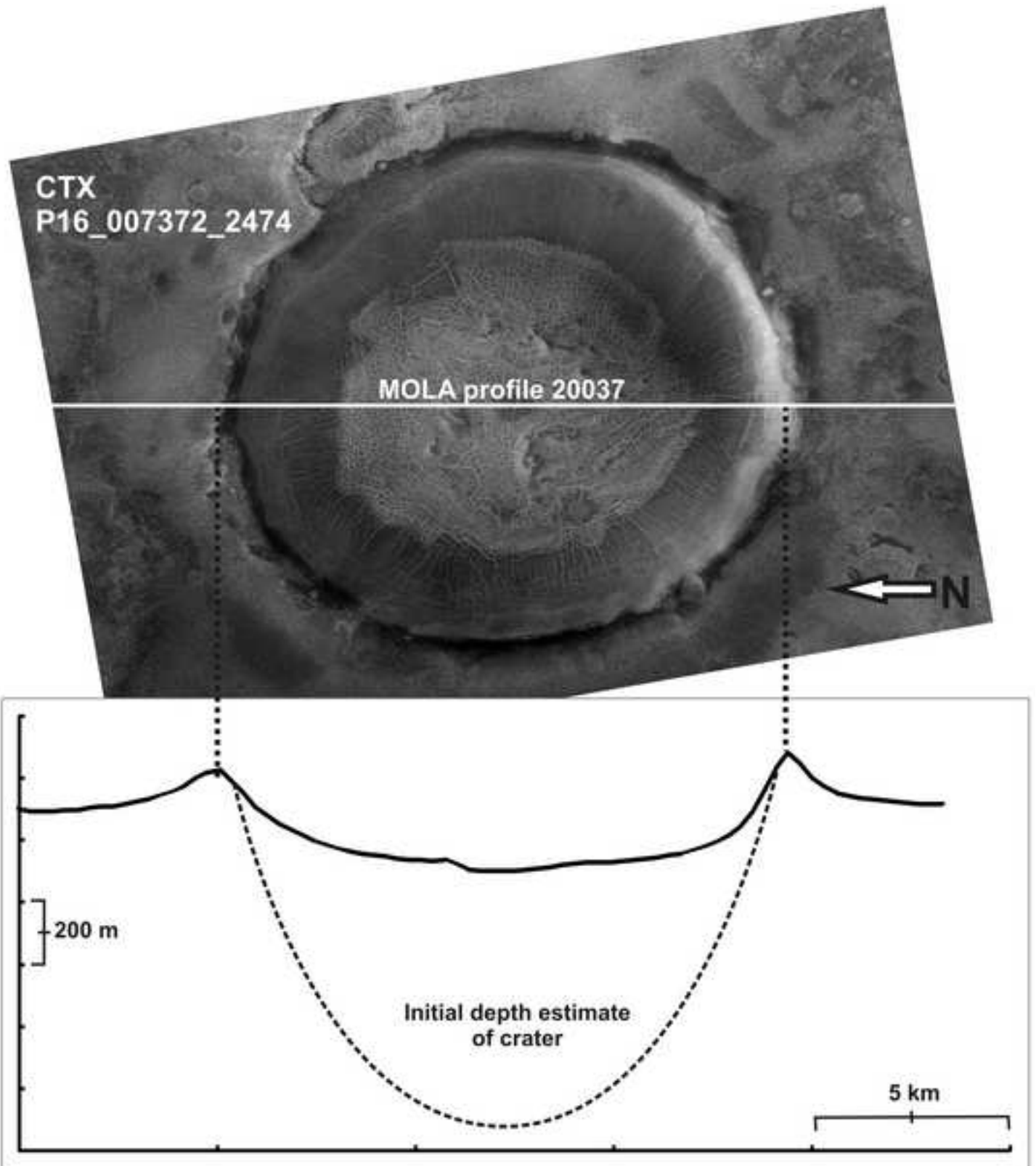


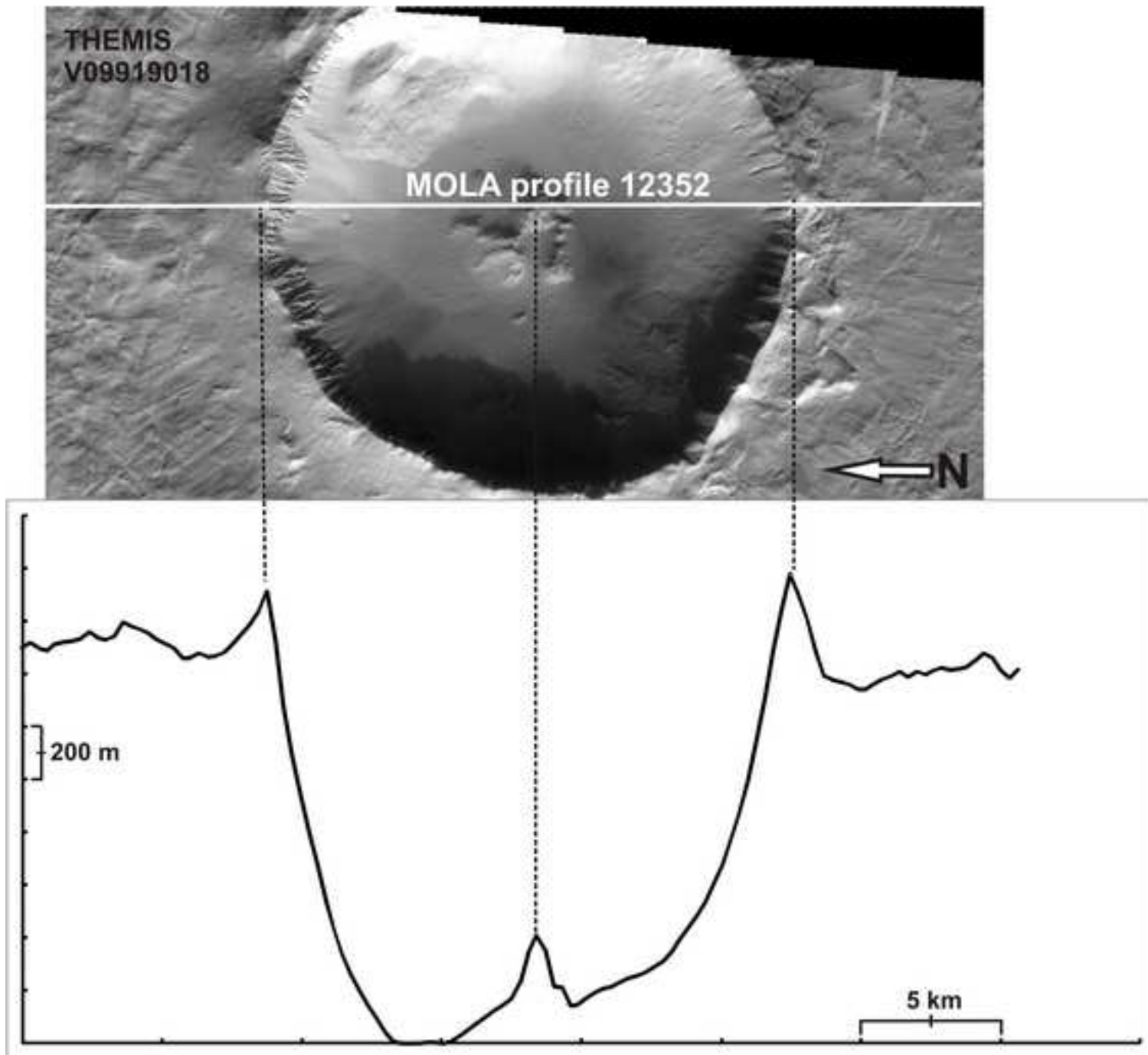




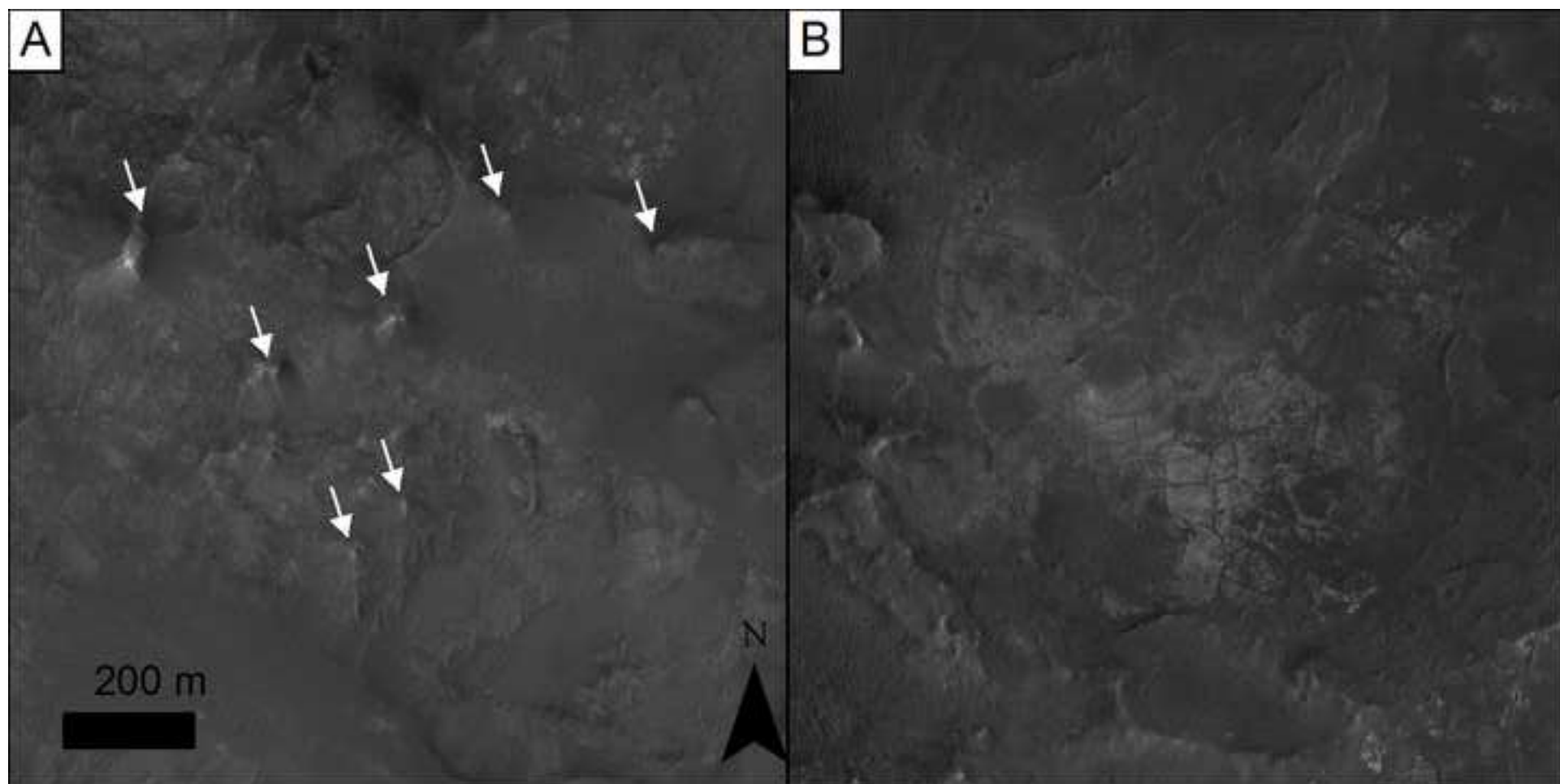


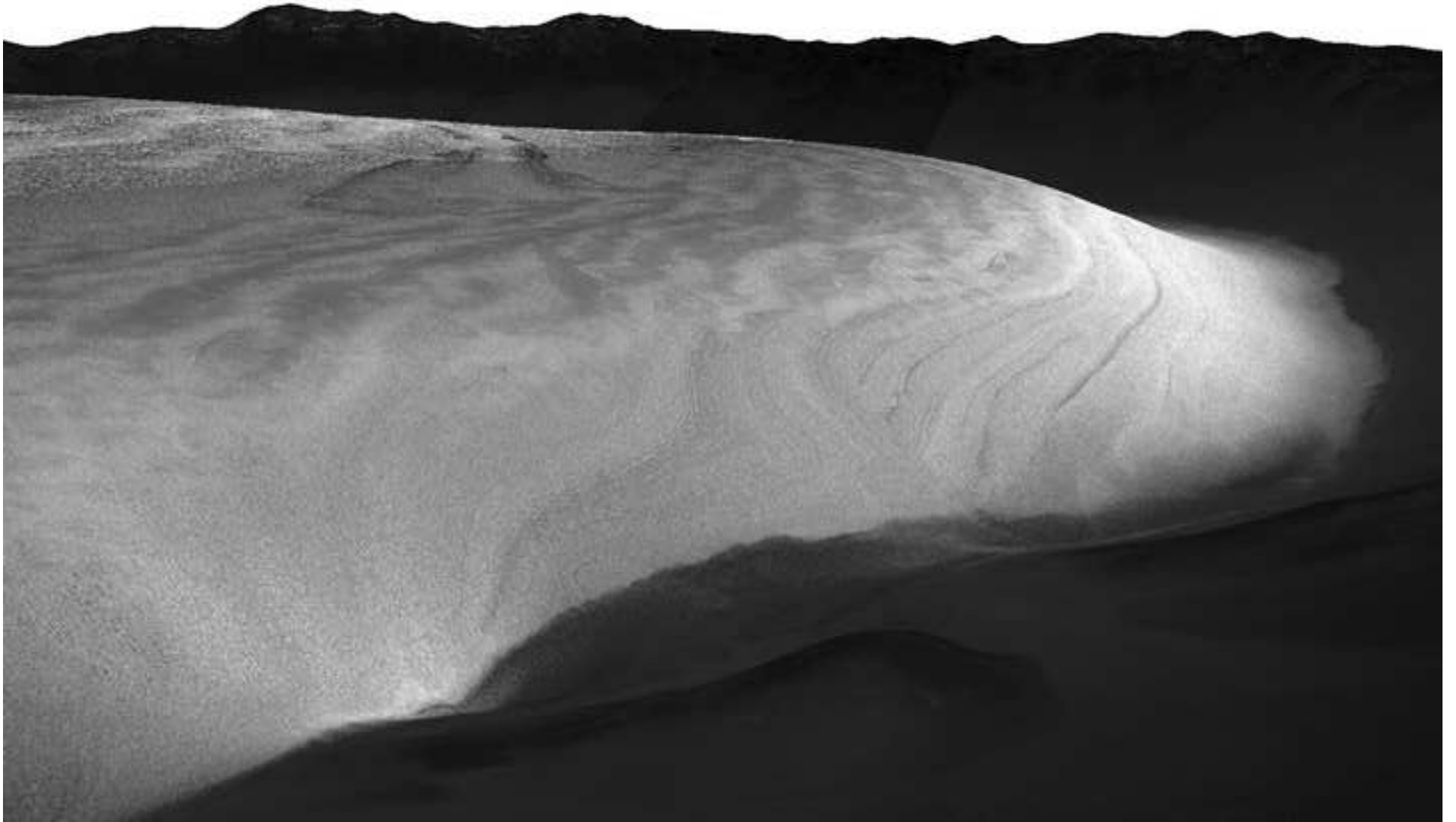












621 **Highlights**

622 >Closed-system pingos (CSPs) are perennial ice-cored mounds>They form from pooled surface  
623 H<sub>2</sub>O and by means of freeze-thaw cycling>Mound-like CSPs occur in 5 highly-filled northern  
624 near-polar impact craters on Mars>Formation hypotheses based on leading alternatives are  
625 shown to be less robust>CSPs need regional boundary-conditions to be wetter/warmer than most  
626 models predict  
627  
628  
629  
630

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