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## ► To cite this version:

R.J. Soare, Susan J. Conway, C. Gallagher, J.M. Dohm. Ice-rich (periglacial) vs icy (glacial) depressions in the Argyre region, Mars: a proposed cold-climate dichotomy of landforms. *Icarus*, 2017, 282, pp.70-83. 10.1016/j.icarus.2016.09.009 . hal-02271715

**HAL Id: hal-02271715**

**<https://hal.science/hal-02271715>**

Submitted on 8 Jan 2021

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***Ice-rich (periglacial) vs icy (glacial) depressions in the Argyre region, Mars:  
a proposed cold-climate dichotomy of landforms***

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**Keyword** - Mars, climate; Mars, surface; Mars, polar geology

36 **ABSTRACT**

37           On Mars, so-called “scalped depressions” are widely observed in Utopia Planitia (*UP*)  
38 and Malea Planum (*MP*). Typically, they are rimless, metres- to decametres-deep, incised  
39 sharply, tiered inwardly, polygonised and sometimes pitted. The depressions seemingly incise  
40 terrain that is *icy* and possibly thermokarstic, i.e. produced by the thermal destabilisation of the  
41 icy terrain. Age-wise, the depressions are thought to be relatively youthful, originating in the Late  
42 Amazonian Epoch.

43           Here, we report the presence of similar depressions in the Argyre region (*AR*) (30-60<sup>0</sup> S;  
44 290-355<sup>0</sup> E). more importantly, we separate and differentiate these landforms into two groups:  
45 *ice-rich periglacial* depressions (Type-1); and, *icy glacial* depressions (Type-2a-c). This  
46 differentiation is presented to the Mars community for the first time.

47           Based on a suite of morphological and geological characteristics synonymous with *ice-*  
48 *complexes* in the Lena Peninsula (eastern Russia) and the Tuktoyaktuk Coastlands (Northwest  
49 Territories, Canada), we propose that the Type-1 depressions are *ice-rich* periglacial basins that  
50 have undergone volatile depletion largely by sublimation and as the result of thermal  
51 destabilisation. In keeping with the terms and associated definitions derived of terrestrial  
52 periglacial-geomorphology, *ice-rich* refers to permanently frozen-ground in which ice lenses or  
53 segregation ice (collectively referenced as *excess ice*) have formed.

54           We suggest that the depressions are the product of a multi-step, cold-climate  
55 geochronology:

- 56           1) Atmospheric precipitation and surface accumulation of an *icy* mantle during recent  
57           high obliquities.

- 58           2) Regional or local triple-point conditions and thaw/evaporation of the mantle, either by  
59           exogenic forcing, i.e. obliquity-driven rises of aerial and sub-aerial temperatures, or  
60           endogenic forcing, i.e. along Argyre impact-related basement structures.
- 61           3) Meltwater migration into the regolith, at least to the full depth of the depressions.
- 62           4) Freeze-thaw cycling and the formation of *excess ice*.
- 63           5) Sublimation of the *excess ice* and depression formation as high obliquity dissipates  
64           and near-surface ice becomes unstable.

65           The Type-2 depressions exhibit characteristics suggestive of *supra-glacial dead-ice*  
66 *basins* and *snow/ice suncups* observed in high-alpine landscapes on Earth, e.g. the Swiss Alps  
67 and the Himalayas. Like the Type-1 depressions, the Type-2 depressions could be the work of  
68 sublimation; however, the latter differ from the former in that they seem to develop within a  
69 glacial-like *icy* mantle that blankets the surface rather than within an *ice-rich* and periglacially-  
70 revised regolith at/near the surface.

71           Interestingly, the Type-2 depressions overlie the Type-1 depressions at some locations. If  
72 the periglacial/glacial morphological and stratigraphical dichotomy of depressions is valid, then  
73 this points to recent glaciation at some locations within the *AR* being precursed by at least one  
74 episode of periglaciation. This also suggests that periglaciation has a deeper history in the region  
75 than has been thought hitherto. Moreover, if the hypothesised differences amongst the Argyre-  
76 based depressions are mirrored in Utopia Planitia and Malea Planum, then perhaps this  
77 periglacial-glacial dichotomy and its associated geochronology are as relevant to understanding  
78 late period landscape-evolution in these two regions as it is in the *AR*.

79

80

## 81 1. Introduction

82 On Mars, depressions that are metre- to decametre-deep, polygonised (and sometimes  
83 pitted) depressions that are rimless, incised sharply, inwardly-terraced or stepped, and  
84 occasionally scalloped, are observed widely in Utopia Planitia (*UP*) (Costard and Kargel, 1995;  
85 Seibert and Kargel, 2001; Morgenstern et al., 2007; Soare et al., 2007, 2008, 2009; Lefort et al.,  
86 2009a; Séjourné et al., 2011, 2012; Ulrich et al., 2010) and Malea Planum (*MP*) (Lefort et al.,  
87 2009b; Zanetti et al., 2010; Wilmes et al., 2012). The depressions are thought to: a) have formed  
88 in the very Late Amazonian Epoch, given the sharpness of their incision, the highly-muted  
89 terrain in which they occur, and sparse cratering; b) reside in *icy* terrain; and, c) be thermally  
90 destabilised and ice-depleted - *thermokarstic* - as the result of near-surface and obliquity-driven  
91 ice instability (Costard and Kargel, 1995; Morgenstern et al., 2007; Soare et al., 2007, 2008,  
92 2009; Lefort et al., 2009a-b; Zanetti et al., 2010; Ulrich et al., 2010; Wilmes et al., 2012). Similar  
93 depressions are observed in and around the Argyre impact-basin region (*AR*) in the southern  
94 hemisphere (30-60<sup>0</sup> S; 290-355<sup>0</sup> E). Some workers suggest that this is a region where near-  
95 surface water ice and surface liquid-water could be meta-stable even under current conditions  
96 (Haberle et al., 2001; Zent et al., 1986, also, Hecht et al., 2002).

97 In the Lena Peninsula (eastern Russia) (e.g. Schirrmeister et al., 2002, 2013; Grosse et al.,  
98 2007) and the Tuktoyaktuk Coastlands (Northwest Territories, Canada) (e.g. Washburn, 1973;  
99 Mackay, 1979; Murton, 1996; Dallimore et al., 2000; Hill et al., 2001; French, 2007) depressions  
100 of the type observed in the *AR*, as well in *UP* and *MP*, often occur in *ice-complexes*. These  
101 complexes or landform assemblages are: *ice-rich* (i.e. containing *ice lenses* and *segregation ice*,  
102 collectively reference as *excess ice*, from metres to decametres of depth); incised by ice-wedge  
103 polygons and polygon trough/junction ponds or pits; punctuated by thermokarstic-terrain (i.e.

104 terrain underlain by excess ice) and rimless depressions or *alases* (where the excess ice has been  
105 lost by evaporation or drainage) (e.g. Schirmer et al., 2002, 2013; Grosse et al., 2007).

106 Other depressions in the AR show morphologies and traits similar in some ways to those  
107 presented above; however, they are distinguishable by the absence of polygonisation,  
108 trough/junction pits and inward-oriented terraces and the presence of sharp rims (in some  
109 instances), bowl-like shape and dense honeycomb-like clustering. Collectively, this second group  
110 of depressions is suggestive of *supra-glacial lake basins* and of *snow/ice suncups* as observed,  
111 for example, in the Swiss Alps (Kääb and Haeberli, 2001; Paul et al., 2007) and the Himalayas  
112 (Benn et al., 2000; Reynolds, 2000).

113 *Supra-glacial lakes* occur in debris-covered *dead-ice* (ice that has been decoupled from  
114 an originating glacier) (Kääb and Haeberli, 2001); here, irregularly-shaped crevasses formed by  
115 the stress of glacial advance and retreat fill with water, derived of melted snow or ice, and evolve  
116 into small metres-deep lakes that are metres to decametres in (long-axis) diameter (Kääb and  
117 Haeberli, 2001). Meltwater drainage or evaporation exposes floor or basin morphologies similar  
118 to those associated with the second group of Mars depressions. Small-sized polygons have not  
119 been reported in the terrain adjacent to the *dead-ice lakes* or *basins* on Earth.

120 *Suncups* comprise sharply-narrow and sub-metre high ridges separated by smoothly-  
121 concave sub-metre bowls or hollows (Betterton, 2001; Herzfeld et al., 2003); it is thought that  
122 they form by the differentiated albeit highly-localised ablation (sublimation or evaporation) of  
123 dirty vs clean snow (Betterton, 2001; Herzfeld et al., 2003; Mitchell and Tiedje, 2010).

124 In this article we have three main aims:

125 1) map the distribution of (**Fig. 1**) and describe the polygonised, tiered and sometimes-  
126 pitted depressions in the AR, defined as Type-1 depressions (**Fig. 2**); discuss their

127 morphological and geological synonymy with the thermokarst terrain on Earth where *ice-*  
128 *complexes* are observed (**Fig. 3**); and, propose a possible periglacial-origin for these  
129 depressions.

130 2) map the distribution of (**Fig. 1**) and describe morphologically similar but  
131 unpolygonised, untiered and unpitted Type-2 depressions in the region (**Fig. 4**); we  
132 propose that these depressions are glacial in origin and analogous to alpine *dead-ice lake*  
133 basins and *suncups* on Earth (**Fig. 5**).

134 3) hypothesise that an endogenic influence could be responsible, at least in part, for the  
135 thermal de-stabilisation required to form the Type-1 depressions.

136 Numerous studies have explored the possibility of freeze-thaw cycling of water affecting  
137 landscape changes throughout the *AR* during the Late Amazonian Epoch: a) clastically sorted,  
138 small-sized ( $\leq \sim 25$  m in diameter) polygons (Banks et al., 2008; Soare et al., 2016); b) clastically  
139 unsorted, small-sized and low-centred polygons (Soare et al., 2014a); c) (possible) hydraulic or  
140 open-system pingos (Soare et al., 2014b); and, d) gelifluction-like lobes (Johnsson et al., 2015;  
141 Soare et al., 2015, 2016). The proposed dichotomy of landforms and associated geochronology  
142 presented here is consistent with this premise and underlines the extent to which relatively-recent  
143 boundary conditions in the *AR* might have been less uniformly cold and dry, perhaps even to the  
144 present day, than is generally thought.

## 145 **2. Definition of key periglacial terms**

146 The proposed differentiation of periglacial from glacial depressions in the Argyre region  
147 can be meaningful only in as much as the key referential or framing terms are identified and then  
148 defined clearly. Towards this end, the generally-accepted usage of these terms in terrestrial  
149 geology and periglacial-geomorphology is our benchmark. We recognise that some workers in  
150 the Mars community of planetary scientists believe that the relevance and viability of definitions

151 derived of terrestrial systems or landscapes is contingent upon their adaptation to the Martian  
152 context (e.g. Byrne et al., 2009; Dundas et al., 2015; Sizemore et al., 2015). However, until a  
153 discrete and thorough discussion on appropriate periglacial-terms and -definitions for Mars  
154 appears in the scholarly literature, deference to the current lexicon of terrestrial geology and  
155 periglacial-geomorphology might be the most prudent course to plot.

## 156 **2.1 Permafrost and excess ice**

157 *Permafrost*, i.e. soil that has been frozen for at least two years, is *ice-rich* if and when it  
158 contains *excess ice* (Harris et al. 1988). *Excess ice* describes *permafrost* those pore space is  
159 exceeded by ice within that body; it comprises discrete *ice lenses* or lenses of *segregation ice*  
160 that range in thickness from hairline to >10m and, typically, are observed in alternating horizons  
161 of ice and soil (Penner, 1959; Harris et al., 1988). Fine-grained soils are particularly adept at  
162 forming *excess ice* because their small pores and pathways induce the movement of unfrozen  
163 water to the freezing front at a rate commensurable with the formation of *ice lenses* (Penner,  
164 1959; Harris et al., 1988). Frost settlement or deflation occurs when *excess ice* thaws and  
165 meltwater pools or is removed from the thaw site is lost by evaporation or drainage (Washburn,  
166 1973; French, 2007).

## 167 **2.2 Thermokarst**

168 Generically, terrain that comprises *ice-rich* permafrost and, is subject to frost settlement  
169 or deflation is referenced as *thermokarst* (e.g. Washburn, 1973, Harris et al. 1988, Murton, 1996;  
170 Dallimore et al., 2000; French, 2007) (**Fig. 3a**). An *alas* is the depression formed by the  
171 surface/near-surface and localised loss of *excess ice* (Harris et al., 1988). If this loss produces a  
172 pond and, subsequently, if the ponded water evaporates or drains episodically, inwardly-oriented  
173 and scalloped-shaped benches or terraces may develop on the basin margins (**Fig. 3b**).



174 The shape (sub-circular to elongate), size (metres to kilometres in long-axis diameter),  
175 depth (sub- to multi-metres) and distribution (individually, clustered or coalesced) of  
176 *thermokarst* landforms mirror the vertical and horizontal distribution of *ice-rich permafrost* in a  
177 landscape and the penetration reach of a thermal wave (e.g. Washburn, 1973, Harris et al. 1988,  
178 Murton, 1996; French, 2007). Terrain punctuated by the presence of *excess ice* is particularly  
179 sensitive to disturbance and volumetric loss if or when seasonal or annual mean-temperatures  
180 rise substantially (e.g. Washburn, 1973; Mackay, 1992; Hill et al., 2001; French, 2007).

### 181 **2.3 Thermal-contraction polygons**

182 Often, *thermokarstic* terrain is incised by small-sized (generally  $\leq 25$  m in diameter) and  
183 non-sorted (thermal-contraction) polygons (e.g. Mackay, 1972, 1992; Rampton, 1988; Hill et al.,  
184 2001; Kääh and Haeberli, 2001) (**Fig. 3b-f**). Thermal-contraction fracturing is the result of  
185 tensile stresses in frozen ground induced by the sharp drop of sub-zero ( $0^{\circ}\text{C}$ ) temperatures  
186 (Lachenbruch, 1962; Harris et al., 1988). Thermal-contraction fractures or cracks neither entail  
187 nor require the availability of liquid water (Lachenbruch, 1962). However, ice wedges and  
188 eventually, ice-wedge polygons, may form in thermal-contraction cracks when, where and when  
189 surface-meltwater migrates and freezes *in situ*.

190 If these ice wedges thaw, meltwater may pool and then pond within the marginal troughs  
191 and junctions that bound the polygons (**Figs. 3c-f**). Impelled by thermal erosion, the ponds  
192 sometimes grow and evolve into small-scale fluvio-lacustrine systems or streams that have a  
193 beaded appearance (**Figs. 3d**) (e.g. Hopkins et al., 1955; Washburn, 1973; Black, 1976; Harris et  
194 al., 1988; French, 2007). They are beaded, as melt-water pools more substantially at polygon  
195 junctions than within polygon troughs, and systemic, in as much as the polygon troughs connect

196 or link individual pools or beads to one another (Washburn, 1973; Harris et al., 1988; French,  
197 2007).

### 198 **3. Methods**

199 In order to identify possible mantle-incising periglacial and glacial depressions within the  
200 *AR*, we performed a systematic survey of the available HiRISE (High Resolution Imaging  
201 Science Experiment) images (n=1044) that cover the region (30-60°S; 290-355°E) (**Fig. 6**). We  
202 excluded depressions that present characteristics consistent with impact craters, i.e. completely  
203 circular with a raised rim (whether ejecta were present or not). HiRISE images are between 25  
204 and 50 cm/pix; they have sufficient resolution to identify the geological context of these  
205 depressions. One of the key-observations that motivated our wider survey was that the  
206 depressions seemingly show different morphologies depending on whether or not they are  
207 spatially associated with polygonally-patterned ground. The presence or absence of metre-scale  
208 polygonally patterned ground can be ascertained with confidence only at the resolution of  
209 HiRISE images. Therefore, although many of the depressions included in this study are visible in  
210 Mars Orbiter Camera, Narrow Angle (MOC-NA; ~1.5 m/pix) or Mars Reconnaissance Orbiter  
211 Context (CTX; 6 m/pix) images, the associated features cannot be identified; hence they are not  
212 encompassed in this study.

213 We use two methods to estimate depression depths. One or the other method was  
214 employed in an opportunistic fashion when the data were available. Firstly, where the  
215 depressions are large enough (at least twice the Mars Orbiter Laser Altimeter (MOLA) shot-  
216 spacing, ~300 m) and if they are also crossed by MOLA tracks, these cross sections are used to  
217 estimate depression depth, as follows. We fit a plane to the points on either side of the depression  
218 (or on one side if both sides were not made of the same material) and measure the maximum

219 vertical-distance between this plane and the MOLA shot located at the lowest elevation within  
220 the depression. Secondly, where the depressions are small we use shadow measurements to  
221 estimate depression depths; however, because such depressions have very shallowly-sloping  
222 walls we perform this analysis only where images are taken with high solar-incidence angles.

223 Shadow measurements are performed according to the method presented in (Dauber et  
224 al., 2014). Briefly, shadows cast by depression walls are measured along the solar azimuth on the  
225 RDR HiRISE image and then converted to height ( $h$ ) by assuming a flat-floored depression and  
226 then applying the following formula:  $h = l_m / \sqrt{(\tan^2 i + \tan^2 e - 2 \tan i \tan e \cos v)}$  where  $l_m$  is the  
227 measured length,  $i$  is the incidence angle,  $e$  is the emission angle and  $v$  is the subsolar azimuth. It  
228 should be noted that for the majority of the images surveyed, we were not able to apply either of  
229 these methods, because of the limitations of these methods, mentioned above.

## 230 **4. Observations**

### 231 ***4.1 Type-1 depressions***

232 Of the 1044 HiRISE images that cover the AR we report twenty-five locations where the  
233 Type-1 depressions are observed (**Fig. 1; Table 1**). These locations overlie thirteen disparate  
234 geological-units that range in age from the late Noachian to the late Hesperian Epochs. Six of the  
235 fourteen locations (cf. Table 1, # 14-15, 17-20) are ( $\sim 48.8\text{-}55.6^{\circ}\text{S}$ ;  $297.5\text{-}307.5^{\circ}\text{E}$ ) are amidst or  
236 adjacent to a geological corridor linking Argyre Planitia to a large basin on its western flank in  
237 the cratered highlands. Dohm et al. (2015) refer to this basin as the Argyre western-margin  
238 paleolake (*AWMP*). Here, linear margins and tectonic structures are widespread; this points to  
239 the possibility of impact-related basement-control of the surface geology (Dohm et al., 2015).  
240 Otherwise, the distribution of the Type-1 depressions shows no apparent latitudinal-constraint or

241 gradient as one would expect were obliquity-driven climate the dominant control of depression  
242 formation (**Fig. 1; Table 1**).

243 The Type-1 depressions (**Fig. 2a-h**) display various plan-forms: circular (**Fig. 2b**) or sub-  
244 circular (**Fig. 2c-d**), tear-dropped (**Fig. 2f**) and, occasionally, scalloped, exhibiting inward-  
245 oriented tiers or terraces (**Fig. 2d**). They are observed individually (**Fig. 2b**), clustered (**Fig. 2c-**  
246 **d**) or coalesced, sometimes in wave-like (planform) patterns of distribution (**Fig. 2e**).  
247 Depression-length (long axes of the depressions defined by the outermost closed-contour line)  
248 ranges from ~85-1000 m; widths range from ~50-500 m. Depression-depths reach ~40m (**Figs.**  
249 **7a-b**); however, it should be noted that we are able to identify only two sites where the  
250 depressions are significantly larger than the MOLA shot spacing and are crossed by MOLA  
251 tracks. Collectively, we ascertain no preferred geographical-orientation amongst individual  
252 depressions, although this could be an artefact of the small sample-size. However, where the  
253 depressions coalesce, each of them display the same (long-axis) orientation (**e.g. Figs. 2c-d**).  
254 Depression margins are continuous albeit rimless, well defined and, often, relatively sharp (**Figs.**  
255 **2c-d**). Generally, depression floors are sloped gently and their gain or loss of elevation follows  
256 the local topography (**Figs. 7a-b**). Some floors, however, are uneven and are covered in part by  
257 rocky debris and boulders (**Fig. 2c**).

258 In all of the Type-1 depressions identified by us, depression-margins, -sides, -floors and  
259 even the terrain beyond the depressions themselves, are incised by small-sized (~5 m) and non-  
260 sorted polygons (**e.g. Figs. 2b-g; cf. Table 1**). Many of these polygons comprise centres  
261 surrounded by marginal metre to sub-metre (diameter) troughs and trough-junctions (**Fig. 2g**).  
262 Some of the intra-depression polygonal troughs and junctions are pitted (**Fig. 2g**). These pits are  
263 circular to sub-circular and measure a metre or more in diameter (**Fig. 2g**). Where the pits are

264 slightly larger than this, the shape of the underlying troughs and/or junctions is distorted, even  
265 obscured (**Fig. 2g**).

266         Some pits are connected; this gives them the appearance of linked beads (**Fig. 2g**).  
267 Occasionally, the connected pits display metre-wide and fan-like features that overtop the trough  
268 margins (**Fig. 2h**). Overall, there seems to be no uniform orientation of pit or trough alignment;  
269 both north-south (or south-north) (**Fig. 2g**) and west-east (or east-west) orientation (**Fig 2g**) are  
270 commonplace, although as noted above with regard to the Type-1 depressions themselves, this  
271 could be an artefact of the small sample-size. Where the pits and cavities are clustered, the  
272 surrounding terrain may form a slight depression (**Fig. 2g**).

273         Typically, the depressions are embedded in a smooth (and relatively light-toned) mantle  
274 that mutes the underlying terrain and topography (**Fig. 8a**). Mantle depth ranges from metres to  
275 decametres (**Figs. 7a-b**). Impact craters are sparse and boulders/rocky terrain are scarce where  
276 the mantle is continuous and relatively thick. Where the depression-dissected mantle is  
277 discontinuous and relatively thin, rocky terrain may be observed adjacent to the mantle. The  
278 latter, invariably, exhibits no depressions (**Fig. 8b**). At some locations the polygonised Type-1  
279 mantle seemingly underlies the Type-2 mantle (**Fig. 4f**).

#### 280 *4.2 Type 2 depressions*

281         Overall, the observed Type-2(a-c) depressions are more numerous than the Type-1  
282 depressions and are located largely to the north of 50<sup>0</sup> S (**Fig. 1; Table 2**). The Type-2(a)  
283 depressions are decametre to kilometre in scale and copy the diverse morphology of Type-1  
284 depressions (**Figs. 4a-c**), except for the absence of scalloped rims, tiered interior slopes, wave-  
285 like planform or interior polygonal-patterning.

286 Like the Type-1 depressions, the Type-2(a) depressions are rimless; they are also  
287 anchored in mantled terrain that is relatively smooth (**Figs. 4b, d-e**), cratered sparsely and absent  
288 of boulders/rocky terrain; however, unlike the Type-1 depressions, neither the 2(a) depressions  
289 nor the terrain incised by them are polygonised at any of the locations observed by us (**Figs. 4a-**  
290 **c**).

291 Type-2(b) depressions comprise multi-metre to decametre-scale pits that are shaped  
292 irregularly and rimmed sharply (**Figs. 4c-d, f**). These pits or hollows occur in dense clusters that  
293 exhibit a honeycomb-like appearance and, often, reside within Type-2(a) depressions. The 2(b)  
294 depressions, like the 2(a) depressions, show smooth textures that are not polygonised. As noted  
295 in the previous section, some Type-2(b) depressions and the Type-2 mantle incised by them  
296 appear to overlie a Type-1 mantle, the latter being identified by its polygonisation (**Fig. 4f**).

297 The Type-2(c) depressions, similarly to the 2(b) depressions, are shaped irregularly, have  
298 raised-rims and display diameters in the multi-metre to decametre range (**Figs. 4g-h**). Where the  
299 distribution of these depressions is dense and ubiquitous, as it may be throughout the inter-crater  
300 plains of the region, the depressions impart a sponge-like texture to the landscape (**Figs. 4g-h**).  
301 The ubiquity of these depressions enables us to estimate their depths using shadow-  
302 measurements on low sun-angle images. For Table 2-location 22 (ESP\_026851\_1445, solar  
303 incidence  $76.7^\circ$ ) we made 100 random measurements of shadows cast by the walls of the  
304 depressions; depression depths range from 0.5-4.7m and the average depth is 2.3 m (**Fig. 9a**). For  
305 Table 2-location 27 (ESP\_028552\_1440, solar incidence  $66.892612^\circ$ ) we made 30 random  
306 measurements; depression depths range from 0.6-3.2 m and the average depth is  $\sim 1.6$  m (**Fig.**  
307 **9b**). The Type-2(c) depressions are observed on impact-crater ejecta (**Fig. 4i**); terrain adjacent to  
308 the ejecta (**Fig. 4i**); and, as noted above, expansively on inter-crater terrain.

### 309 **4.3 Type-1 depressions: uniquely different from Type-2 depressions**

310 In the main, there are five key traits or characteristics that differentiate the Type-2(a-c)  
311 from the Type-1 depressions. First, the Type-1 depressions are polygonised, as is the terrain  
312 adjacent to the depressions; by means of contrast, the Type-2 depressions are unpolygonised in  
313 all observed instances, as is the terrain adjacent to them. Second, the Type-1 depressions exhibit  
314 pitting, sometimes beaded, within polygon-margin troughs and trough-junctions. Pitting of this  
315 type is not observed in conjunction with any of the Type-2 depressions. Third, some of the Type-  
316 1 depressions, especially those that exhibit wave-like clustering, are scalloped and show inward-  
317 oriented tiers or terraces; none of the observed Type-2 depressions exhibit similar traits. Fourth,  
318 the bowl-like and multi- to decametre-wide Type-2(b) depressions often are nested within the  
319 Type-2(a) depressions but never within the Type-1 depressions. Fifth, where the Type-2 and  
320 Type-1 mantles (and their spatially-associated depressions) are observed concurrently in a  
321 landscape the Type-1 mantle underlies the Type-2 mantle in all instances.

### 322 **5. Type-1 depressions and possible ice-rich (periglacial) complexes**

323 The spatial-synonymy of the Type-1 depressions and the (sometimes) pitted, (invariably)  
324 polygonised-terrain in the Argyre region (within and adjacent to the Type-1 depressions) mirrors  
325 that of thermokarst/alas assemblages and polygon-margin pits in periglacial, *ice -rich complexes*  
326 on Earth. As noted above, the latter develop a) when and if *excess ice* is present in the near-  
327 surface permafrost, sometimes to decametres of depth; and, b) when and if the *excess ice*  
328 undergoes heat-induced thermal destabilisation and is removed from the permafrost by  
329 evaporation or drainage.

330 The possible origin and loss of *excess ice* as a precursive condition to the formation of  
331 Type-1 depressions is neither simple nor straightforward. In order to frame our hypothesis aptly,

332 we propose a (simplified) four-step meteorological and geological chronology. It coalesces  
333 generally-accepted assumptions concerning obliquity-related *icy* mantle formation in the Late  
334 Amazonian Epoch with the requirements of forming an *ice-complex* derived of freeze-thaw  
335 cycles in periglacial landscapes on Earth. *Ice complexes* formed entirely by means of vapour-  
336 diffusion cycles have yet to be observed on Earth.

337 (Step-1): A water- or dusty-ice mantle forms at the mid to high latitudes of both  
338 hemispheres; it is the obliquity-driven product of atmospheric precipitation and surface  
339 accumulation (e.g. Mustard et al., 2001; Milliken et al., 2003; Head et al., 2003, 2006; Tanaka et  
340 al., 2005; Forget et al., 2006; Madeleine et al., 2009, 2014; Schorghofer and Forget, 2012). This  
341 mantle predates the very Late Amazonian Epoch mantle commonly referenced in the literature  
342 by these and other workers but would be consistent with the origin, composition, landscape  
343 characteristics and geographical distribution of the current mantle discussed by them.

344 The observed and deduced evidence favouring an *icy* composition for the later mantle in  
345 the *AR* is as follows: (1) the elevated occurrence of near-surface water ice (inferred from the  
346 Mars Odyssey gamma-ray and neutron-spectrometer data); (2) landforms whose morphology  
347 collectively implies a glacial landscape, i.e. moraine- and esker-like ridges, lobate-debris aprons  
348 (i.e. possible debris covered rock-glaciers) and semi-circular (cirque-like) embayments; (3) the  
349 latitudinal constraint/distribution of the observed mantled-terrain, predicted by models linking  
350 ground-ice stability with recent changes in the obliquity and spin parameters of Mars (Banks et  
351 al., 2008, 2009; Wilmes et al., 2010; Zanetti et al., 2012; El Maarry et al., 2013).

352 (Step-2): As Mars moves towards high obliquity the early or antecedent mantle thaws and  
353 generates meltwater, especially in areas such as the *AR* where water could be metastable even  
354 under current conditions (e.g. Haberle et al., 2001; Zent et al., 1986; also, see Hecht, 2002);



355 mantle thaw also could be produced endogenically were deeply-seated heat to be delivered to the  
356 surface by means of Argyre (impact-related) geothermal pathways, identified by linear margins  
357 and tectonic structures at the surface (Dohm et al., 2015; Williams et al., 2016; also, Soare et al.,  
358 2014).

359 (Step-3): The meltwater migrates into the underlying fine-grained regolith (Soare et al.,  
360 2016) and undergoes episodic freeze-thaw iterations at discrete and disparate freezing-fronts.  
361 This forms multiple *ice lenses* or layers. Basaltic regolith, thought to be commonplace in the AR  
362 (e.g. Bandfield and Rogers, 2008), would be an ideal medium for this type of preferential freeze-  
363 thaw cycling and the formation of *excess ice*.

364 (Step-4): The ice degrades or ablates, probably by sublimation, as high obliquity wanes  
365 (e.g. Morgenstern et al., 2007; Lefort et al., 2009a-b; Séjourné et al., 2011, 2012) or in response  
366 to highly-localised endogenic forcing (Dohm et al., 2015); alas-like Type-1 depressions are  
367 formed. Subsequently, thermal-contraction cracking polygonises the depressions and the  
368 surrounding terrain (Costard and Kargel, 1995; Seibert and Kargel, 2001; Mangold et al., 2005;  
369 Levy et al., 2009). In turn, small-scale pits and linked beaded-troughs form within polygon  
370 margins; this could be the work of near-surface ice being removed from the regolith by  
371 sublimation or thaw/evaporation (Wan Bun Tseung and Soare, 2006; Soare et al., 2008; Séjourné  
372 et al., 2010; 2011, 2012).

## 373 **6. Type-2 depressions and a high-alpine (glacial) analogue**

374 A follow-up cycle of *icy* mantle-formation and -degradation occurs in the more recent  
375 past. As the mantle forms it blankets the terrain in which the polygonised Type-1 depressions  
376 developed and subsequently, at an indeterminately later time, begins to sublimate; dead-ice (like)  
377 basins and snow/ice suncups are an end-product of this sublimation (Massé et al., 2010;

378 Mangold, 2011). Further degradation ablates the mantle sufficiently to expose the underlying  
379 Type-1 depressions, as well as the polygonised terrain that incises and encompasses them.

## 380 **7. Discussion and conclusion**

381 On the basis of disparate morphological-traits, trait-assemblages and landscape-  
382 characteristics we have identified two different depression-types (Type-1 and Type-2) in the AR.  
383 We propose that the first depression-type approximates (periglacial) *alases* on Earth, whereas the  
384 second type exhibits striking similarities with terrestrial (supra-glacial) *dead-ice basins* and  
385 *suncups*.

386 The glacial pathway that produces the Type-2 depressions is somewhat simpler than the  
387 one associated with the periglacial formation of the Type-1 depressions; it is also largely  
388 consistent with the widely-held beliefs about obliquity-driven mantle formation and degradation  
389 in the Late Amazonian Epoch. Moreover, the plausibility of the glacial pathway is not contingent  
390 upon triple-point conditions being reached.

391 By means of contrast, the periglacial pathway that engenders the formation of the Type-2  
392 depressions requires multiple episodes of freeze-thaw cycling (perhaps facilitated by the  
393 presence of brines in the regolith), antecedent mantle-formation and -degradation, and the  
394 accumulation of *excess ice* to decametres of depth.

395 Some preliminary work has explored a possible formation-pathway for near-surface *ice*  
396 *lenses* and *excess ice* based on absorption/diffusion cycles (Dundas, 2015; Sizemore, 2015).  
397 However, whether this pathway is robust enough to form excess ice to the depths associated with  
398 the largest of the Type-1 (alas-like) depressions is an open question.

399 The observed superposition of the Type-2 mantle and associated depressions on  
400 polygonised Type-1 terrain suggests that discrete and multiple episodes of relatively-recent

401 mantle formation can be identified, separated stratigraphically, and linked to disparate cold-  
402 climate origins. It also highlights the possibility that significant thermokarstic-revisions of the  
403 regional landscape in the *AR* predate the most recent period of glaciation.

404         Interestingly, some of the Type-1 depressions exhibit polygon-junction and trough-pitting  
405 as well as some small-scale beading comprised of interconnected polygon-junction and polygon-  
406 trough pits. Similar morphologies are observed in *ice-rich* landscapes on Earth and are diagnostic  
407 of: a) antecedent polygonised ice-wedging; b) ice thaw; c) the formation, ponded accumulation  
408 and eventual evacuation of ice-derived meltwater by evaporation or drainage; and, d) the  
409 organisation of localised fluvio-lacustrine (periglacial) systems. At some locations small fan-like  
410 features overtop the beaded troughs; this points to the possibility of highly-localised debris flow.

411         The relative absence of uniformity in the orientation of the junction-pit linked-  
412 assemblages argues against the possibility of formation by aeolian deflation (Morgenstern et al.,  
413 2007; Séjourné et al., 2010) or by tectonic/structural forces (Lefort et al., 2009a). But even if the  
414 pits and beading are the work of sublimation, not evaporation or drainage, the morphologies of  
415 the pits and beads points strongly towards the presence of near-surface ground-ice, a key marker  
416 of an ice-rich landscape.

417         The absence of an apparent latitudinal-constraint on the distribution of the Type-1  
418 depressions, as well as the paucity of the Type-1 depressions compared to the Type-2  
419 depressions, is enigmatic. Under current or recent aerial or sub-aerial boundary conditions, ice  
420 stability is thought to increase with latitude (e.g. Mellon and Jakosky, 1995; Head et al., 2003;  
421 Morgenstern et al., 2007; Lefort et al., 2009b; Zanetti et al., 2010; Dundas, 2015). If the  
422 ascription of a thermokarstic origin to the Type-1 depressions is valid, then one would expect the  
423 number of Type-1 depressions to decrease with latitude, in line with an increase of ice stability.

424 On the other hand, the small number of observed Type-1 depressions could be the result  
425 of highly-localised and favourable surface-pressures and temperatures in the *AR* when the  
426 depressions formed, as could be inferred from Haberle et al., (2001) and Zent et al., (1986), also  
427 Hecht (2002).

428 An endogenic origin of thermal instability ought not to be discounted either. A few Type-  
429 1 depressions are clustered in the area of the *AWMP*. Here, linear margins and tectonic structures  
430 are widespread and, as noted above, some recent work has hypothesised a connexion between  
431 deeply-seated heat, possible impact-related geothermal pathways and ice instability at/near the  
432 surface in this and other areas of the *AR* (Dohm et al., 2015; Williams et al., 2016; also, Soare et  
433 al., 2014).

434 Lastly, the surface coverage of the Argyre impact-basin floor by the *HiRISE* imagery is  
435 poor and small in scale. Perhaps the small population of observed Type-1 depressions is simply  
436 an artefact of this poor coverage.

437 However, were the presumed differences between the two depression-types in the *AR*  
438 valid and mirrored in Utopia Planitia and Malea Planum, then perhaps the commonly-held belief  
439 that the *UP* and *MP* depressions are rooted directly in an *icy* mantle ought to be revisited.

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#### 648 **Acknowledgements**

649 RJS thanks Dawson College, in particular, D. Gauvin and L. Bennett, for a professional  
650 development leave that enabled him to present some of the ideas in this article precursively at the  
651 Nantes EPSC in October, 2015.

#### 652 **Figures**

653 **Fig. 1**

654 Geological-unit map of the Argyre impact-crater and surrounding region of Mars  
 655 (adapted from Dohm et al., 2015). The global geological-map is shown for areas outside  
 656 of the Dohm et al. (2015) map. Type-1 depressions highlighted in orange; Type-2  
 657 depressions (shown in Fig. 4) highlighted in pink.

658 **Fig. 2**

659 **(a)** Type-1 (depression) morphologies and distribution (context-image). **(b)** Circular  
 660 depression. Note the polygonised terrain surrounding the depression and the polygonised  
 661 depression-walls and -floors. **(c)** Four coalesced (sub-circular) depressions. Note the E/W  
 662 or W/E latitudinal orientation of their collective long axes. **(d)** Sub-circular depressions  
 663 that exhibit coalescence, scalloping and some wave-like (planform) distribution **(e)**  
 664 Coalesced depressions with more extensive wave-like distribution **(a-e:** HiRISE image  
 665 ESP\_011319\_1305; 298.954<sup>0</sup>E, 49.001<sup>0</sup>S; res. 50cm/pixel; NASA/JPL/University of  
 666 Arizona). **(f)** Tear-drop shaped depression with longitudinally-orientated long-axis  
 667 (HiRISE image ESP\_013890\_1240; 307.523<sup>0</sup>E, 55.615<sup>0</sup>S; res. 50cm/pixel;  
 668 NASA/JPL/University of Arizona). **(g)** Depression with pitted and deformed polygon-  
 669 margin troughs and junctions. Note the clustering and branching of these features  
 670 (HiRISE image PSP\_006176\_1225.323.637<sup>0</sup>E, 57.130<sup>0</sup>S; res. 50cm/pixel;  
 671 NASA/JPL/University of Arizona). **(h)** Polygon troughs with N/S orientation overtopped  
 672 by small fan-like structures (HiRISE image PSP\_006176\_1225).

673 **Fig. 3**

674 **(a)** Thermokarst lake/alas (light-coloured and unvegetated patches of terrain)  
 675 assemblages in the Tuktoyaktuk Coastlands. **(b)** Archetypal recession of a thermokarst-  
 676 lake margin and the associated scalloping of that margin. **(c)** Thermokarst lake/alas

677 assemblage. Note, 1. the receding lake-margin (top-left corner) and the subsequential  
 678 polygonisation of the newly exposed lake-basin floor; and 2. the formation of a beaded  
 679 fluvial-channel that meanders through interconnected polygon-margins at the right flank  
 680 of the thermokarst lake. **(d)** Development of landscape-wide fluvial systems by means of  
 681 interconnected polygon-troughs. **(e)** Small-scale pooling of meltwater at polygon margins  
 682 on alas floors. **(f)** Convergence of pools and the formation of meltwater ponds. All air-  
 683 photos are of the Tuktoyaktuk Coastlands (Northwest Territories, Canada) between  
 684 Inuvik and Tuktoyaktuk. Image credits: R. Soare.

685 **Fig. 4**

686 **(a-c)** Type 2(a) depressions: circular, sub-circular and tear-dropped; rimless; and,  
 687 decametres hundreds of metres in diameter (HiRISE images ESP\_038785\_1390;  
 688  $334.041^{\circ}$  E,  $40.881^{\circ}$  S; res. 25 cm/pixel; PSP\_007824\_1420;  $322.026^{\circ}$  E,  $37.895^{\circ}$  S; res.  
 689 50cm/pixel; ESP\_021734\_1460;  $353.240^{\circ}$  E,  $33.752^{\circ}$  S; 25 cm/pixel;  
 690 NASA/JPL/University of Arizona). **(d, also c, f)** Type 2(b) depressions: smaller scale  
 691 than Type 2(a), rimmed and, often, clustered densely on the floor and walls of the latter  
 692 ESP\_021734\_1460;  $353.240^{\circ}$  E,  $33.752^{\circ}$  S; 25 cm/pixel; NASA/JPL/University of  
 693 Arizona). **(e, also b, d, f)** Type 2 lightly-toned and mantled-terrain. Note the absence of  
 694 cratering and the mutedness of the underlying topography (HiRISE image  
 695 PSP\_007824\_1420;  $322.026^{\circ}$  E,  $37.895^{\circ}$  S; res. 50 cm/pixel; NASA/JPL/University of  
 696 Arizona). **(f)** Type 2(a) depression incised by multiple Type 2(b) depressions, both of  
 697 which overlie a Type 1 depression (as marked by the dark-toned and polygonised strip of  
 698 terrain on the left-hand side of the image). Here the Type-2 mantle seemingly has  
 699 contracted, possibly ablated, and revealed the underlying dark-toned Type-1 terrain that  
 700 might not be visible otherwise (HiRISE image PSP\_007033\_1445;  $321.183^{\circ}$ , E  $35.000^{\circ}$

701 S; 50 cm/pixel; NASA/JPL/University of Arizona). **(g-h)** Type 2(c) depressions: possible  
702 example of mantle degradation, with (g) showing less degradation than (h) (HiRISE  
703 images ESP\_028552\_1440; 339.485<sup>0</sup>, E 35.640<sup>0</sup> S; 50cm/pixel; ESP\_026851\_1445;  
704 333.395<sup>0</sup>, E 35.002<sup>0</sup> S; 25 cm/pixel; NASA/JPL/University of Arizona). **(i)** Type 2(c)  
705 depressions on the ejecta of an impact crater (HiRISE image ESP\_022315\_1440;  
706 330.846<sup>0</sup>, E 35.843<sup>0</sup> S; 25 cm/pixel; NASA/JPL/University of Arizona).

707 **Fig. 5**

708 Glacial (dead-ice) thermokarst-lake set in glacial debris/overburden (basin area =  
709 ~10,000m<sup>2</sup>; the height of the ice-front to the left is >10m (Kääb and Haeberli, 2001;  
710 copyright by the Regents of the University of Colorado). Here, lake formation is  
711 triggered by thaw. We hypothesise that morphologically similar dead-ice features, i.e.  
712 thermokarst basins, could have formed in the AR by means of ice-sublimation. **(b)** Alpine  
713 suncups (Mather Pass, California). Image credit: [http://www.ultralight](http://www.ultralightbackpacker.com/index.html)  
714 [backpacker.com/index.html](http://www.ultralightbackpacker.com/index.html).

715 **Fig. 6**

716 Overview of the HiRISE images surveyed and the sites identified with Type-1 and Type-  
717 2 depressions. Background THEMIS-Day IR Global mosaic from ASU. The geographic  
718 locations of Figs. 2, 4, 7 and 8 and their sub-figures are shown and labelled in black.

719 **Fig. 7**

720 Topographic profiles of Type-1 depressions with context images. On each topographic  
721 profile the black points are Mars Orbiter Laser Altimeter (MOLA) shots; the grey lines  
722 are linear interpolations across the depressions, using the three points adjacent to the  
723 depression boundary (excluding obvious non-mantled hills). Labels give the maximum



724 distance between the interpolated line and the MOLA data. **(a)** CTX image  
 725 B17\_016132\_1327\_XN\_47S061W with superposed MOLA shot points (in purple)  
 726 obtained from the PDS; the outline of HiRISE image ESP\_011319\_1305 (in red) at site 6  
 727 and the locations of the topographic profiles shown below (in black). **(b)** CTX image  
 728 P15\_007033\_1429\_XN\_37S038W with superposed MOLA shot points (in purple)  
 729 obtained from the PDS; the outline of HiRISE images ESP\_016197\_1445 and  
 730 PSP\_007033\_1445 (in red) at site 1; and, the locations of the topographic profiles shown  
 731 below (in black).

732 **Fig. 8**

733 **(a)** Mid-latitude valley floor covered by terrain that is smooth, i.e. mantled, albeit  
 734 lineated; boulders are sparse (ESP\_013890\_1240; 307.523<sup>0</sup>E, 55.615<sup>0</sup>S; res. 50 cm/pixel;  
 735 NASA/JPL/University of Arizona). **(b)** Mid-latitude mantled terrain in Charitum  
 736 Montes; note the relatively steep and abrupt change of elevation where the putative  
 737 mantle ends and the rocky terrain begins (ESP\_032628\_1275; 300.048<sup>0</sup>E, 52.398<sup>0</sup>S; res.  
 738 50 cm/pixel; NASA/JPL/University of Arizona).

739 **Fig. 9**

740 **(a)** HiRISE image ESP\_026851\_1445 (Table 2-location 22, solar incidence 76.7°), red  
 741 crosses mark the locations where we made 100 random measurements of shadows cast by  
 742 the walls of the Type-2c depressions. **(b)** HiRISE image ESP\_028552\_1440 (Table 2-  
 743 location 27, solar incidence 66.892612°), red crosses mark the locations where 30  
 744 random measurements are made.

Figure

**Legend**

Type 1 depressions

Type 2 depressions

**Geological Units**

**Amazonian/Hesperian**

AHTp, Thaumasia plateau SE

HAb4a, Argyre basin member 4a

**Hesperian/Noachian**

HNh4, Highlands member 4

HNh3, Highlands member 3

HNTTh, Thaumasia highlands

**Noachian**

NAb4b, Argyre basin member 4b

NAb3, Argyre basin member 3

NAb2, Argyre basin member 2

NAb1, Argyre basin member 1

NArsp, Argyre rim smooth plains materials

NAbr, Argyre basin and rim materials

NArb, Argyre rim and basin materials

NAr, Argyre rim materials

Nh2, Highlands member 2

Nh1, Highlands member 1

Nhb, Highlands basins materials

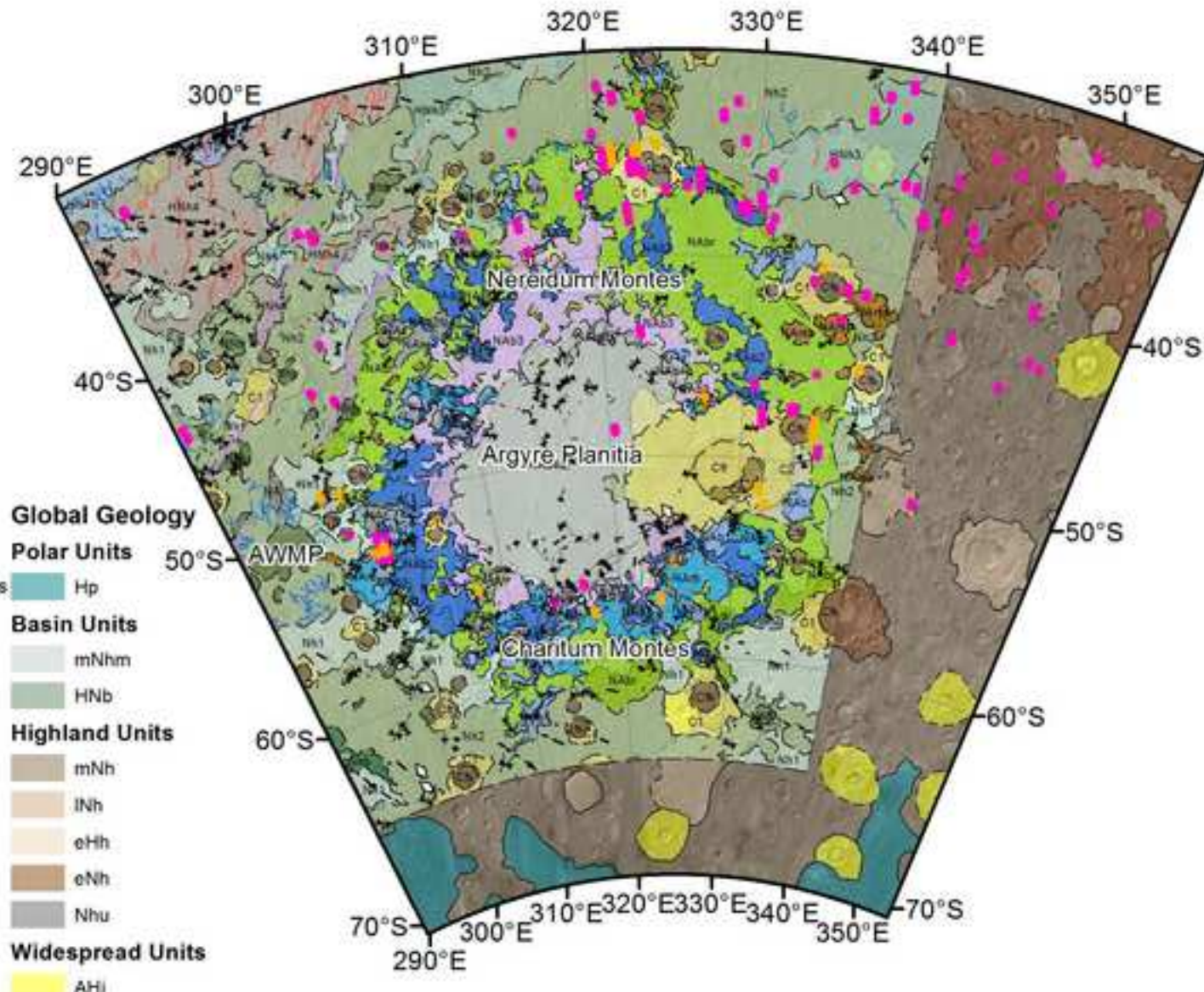
**Crater Units**

Cfr, Rough crater floor materials

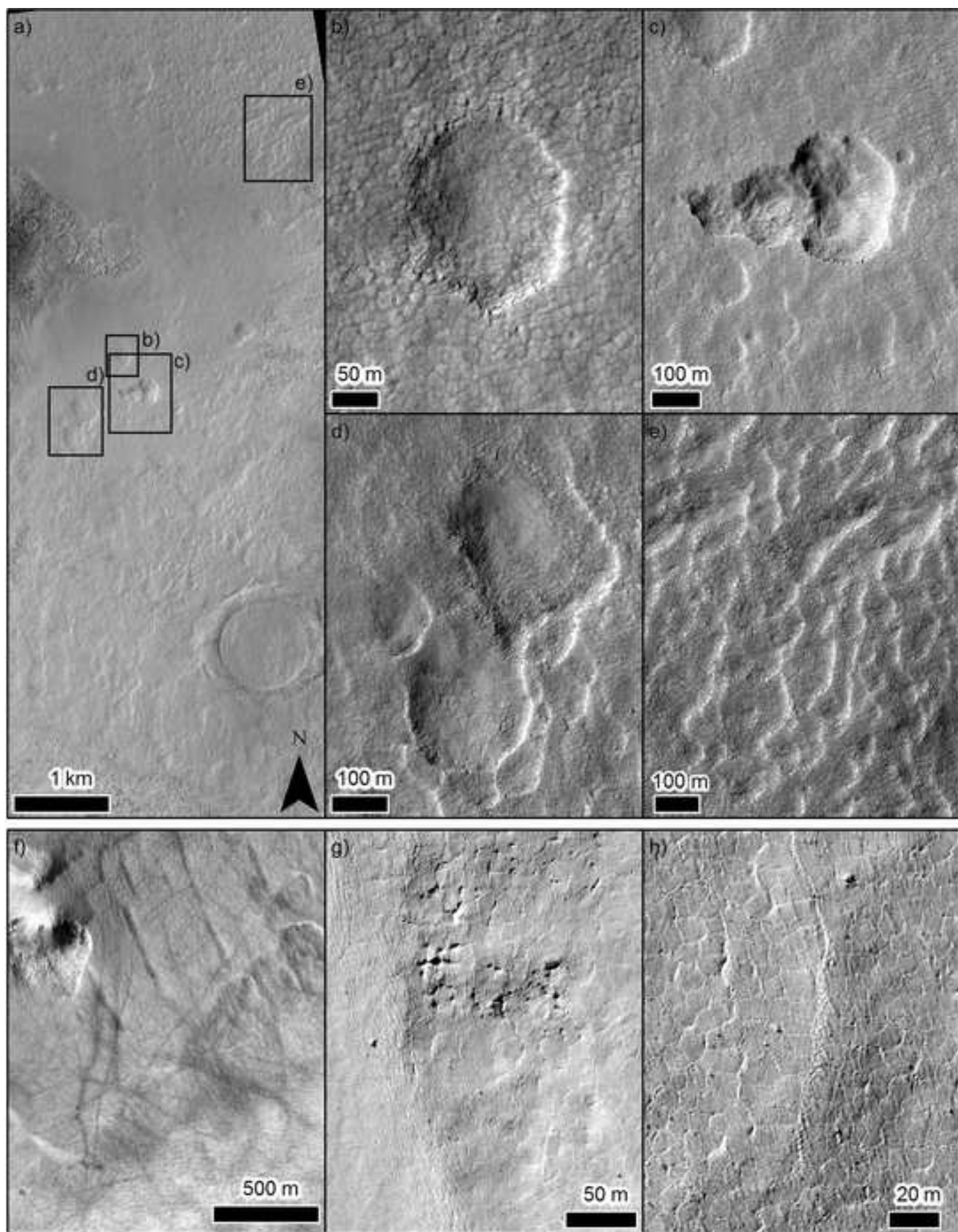
Cfs, Smooth crater floor materials

C2, Young crater materials

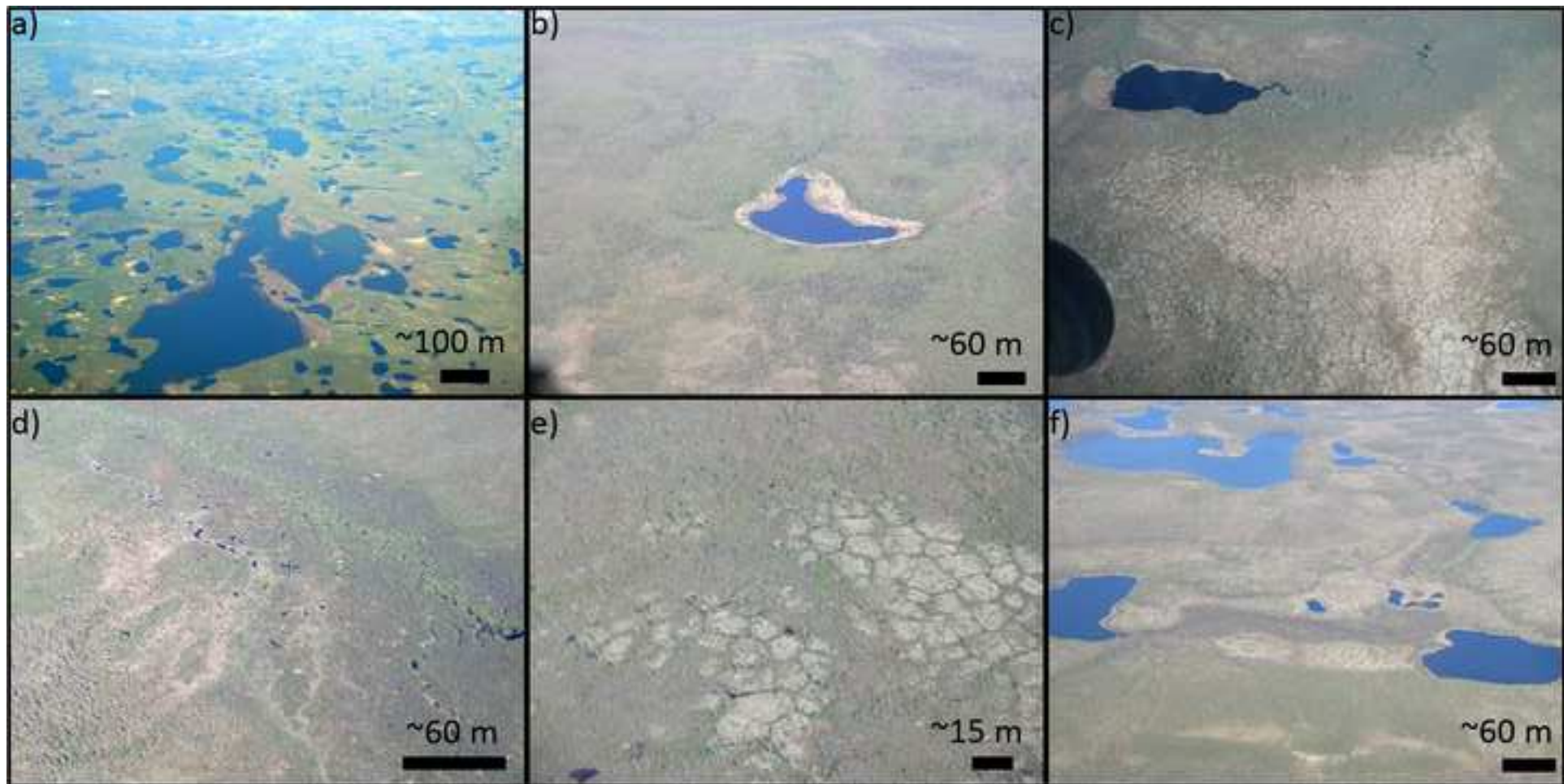
C1, Old crater materials



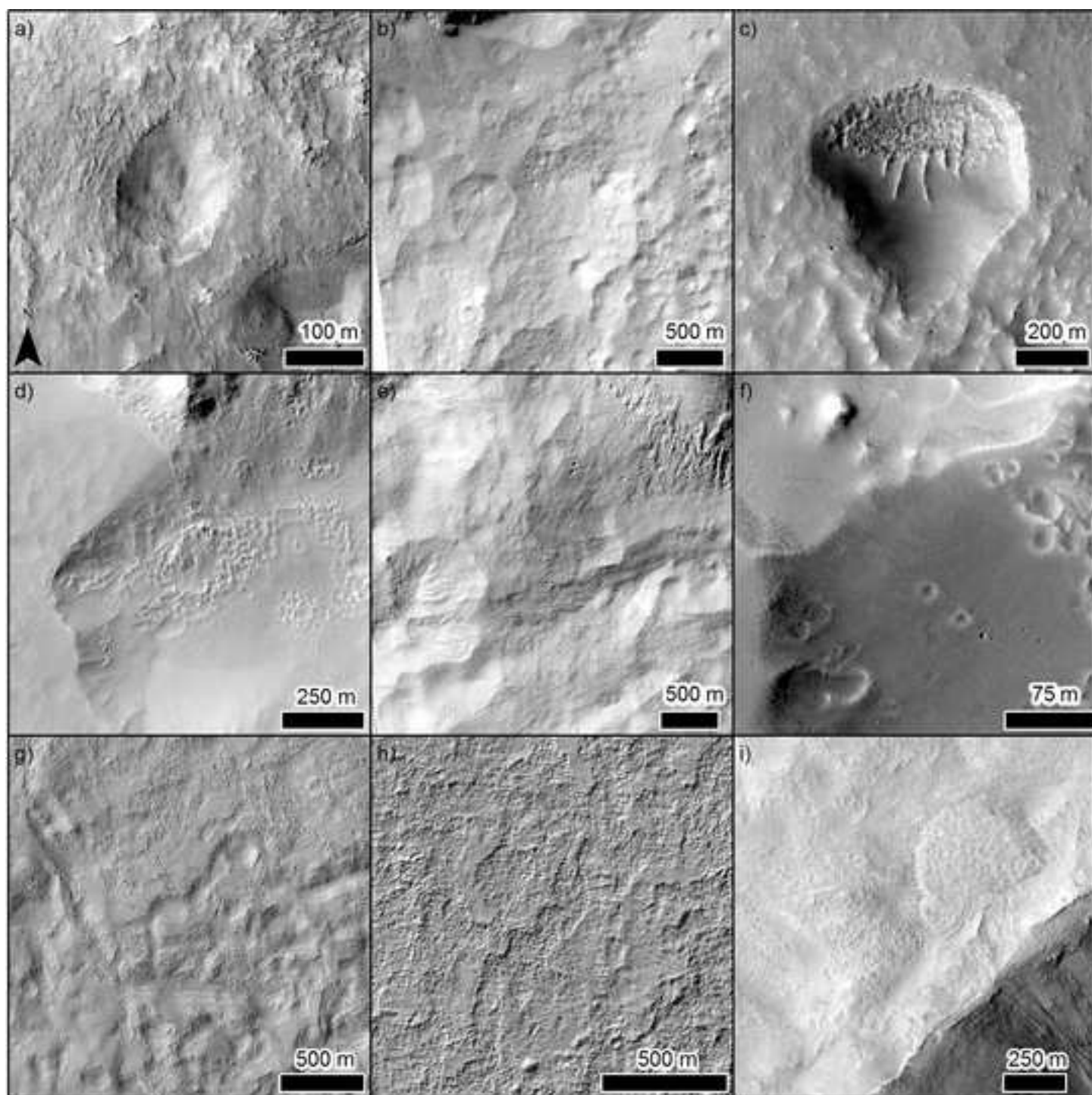
Figure

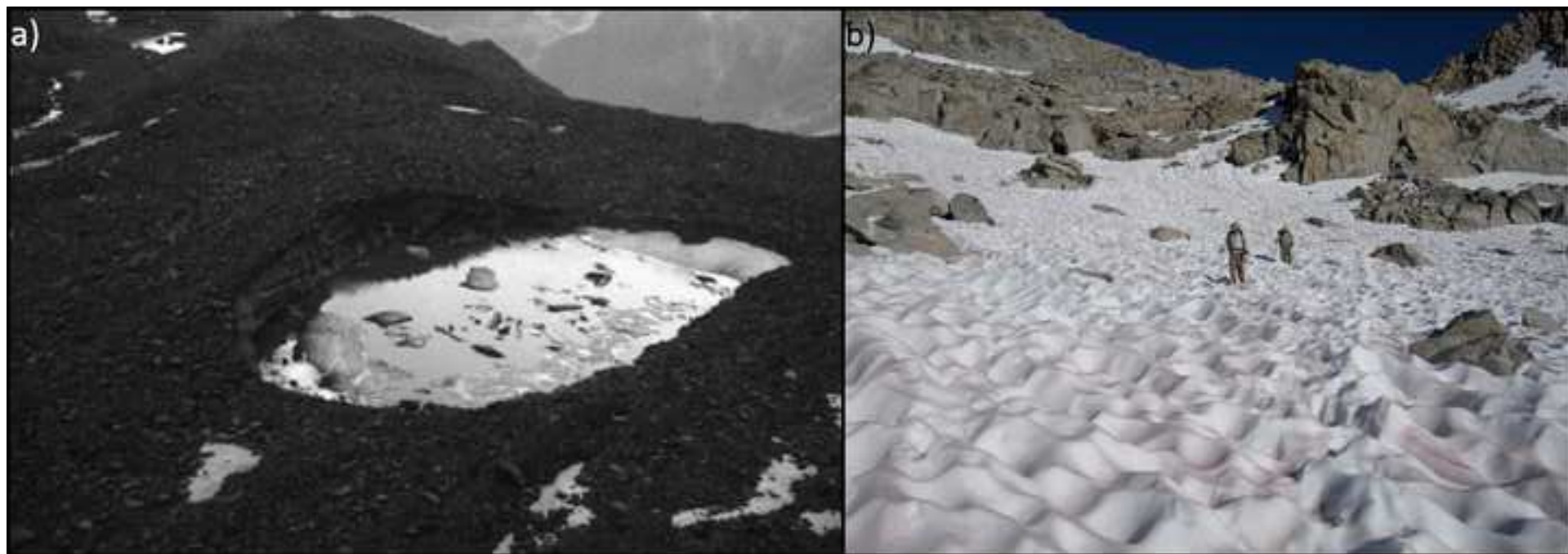


Figure

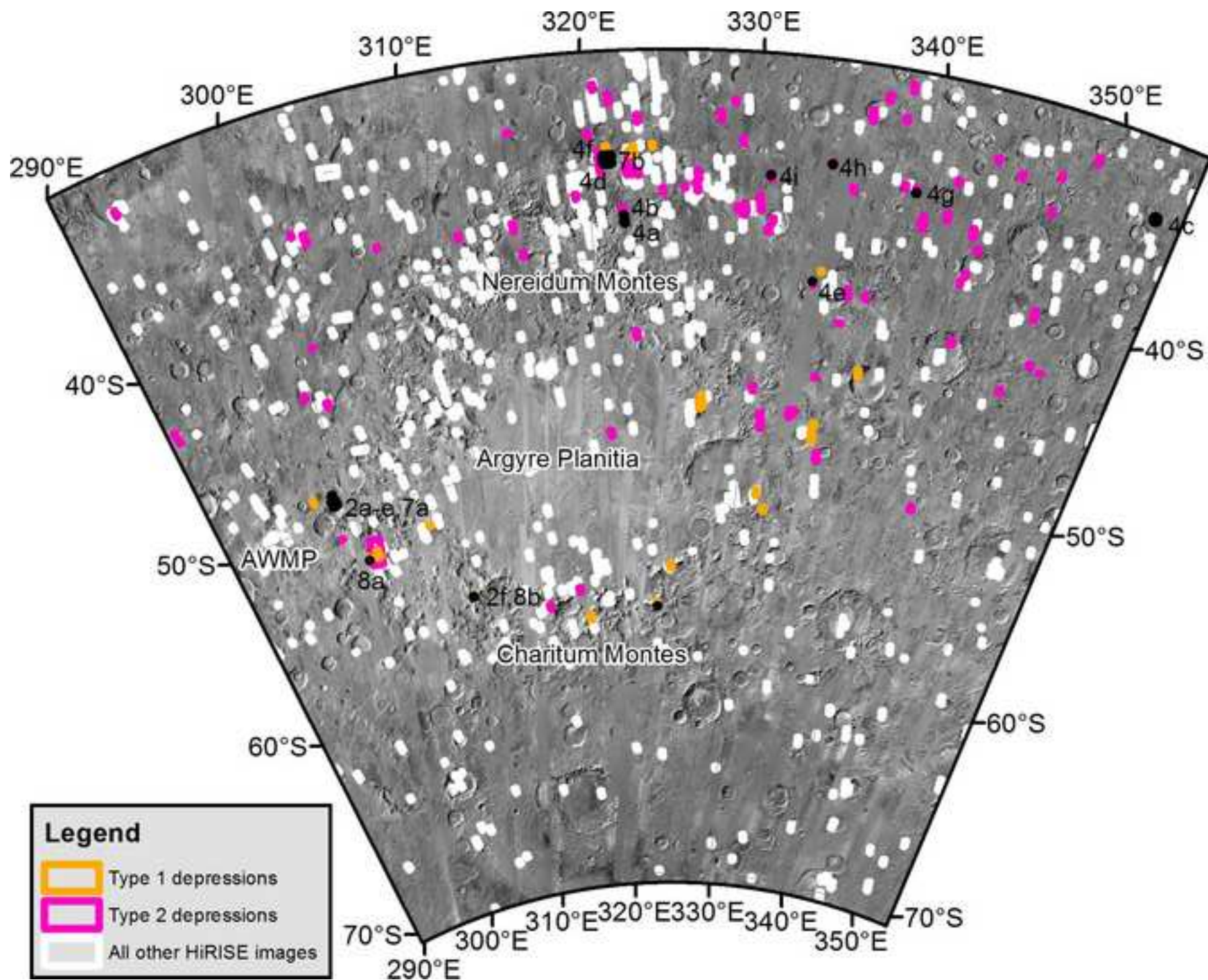


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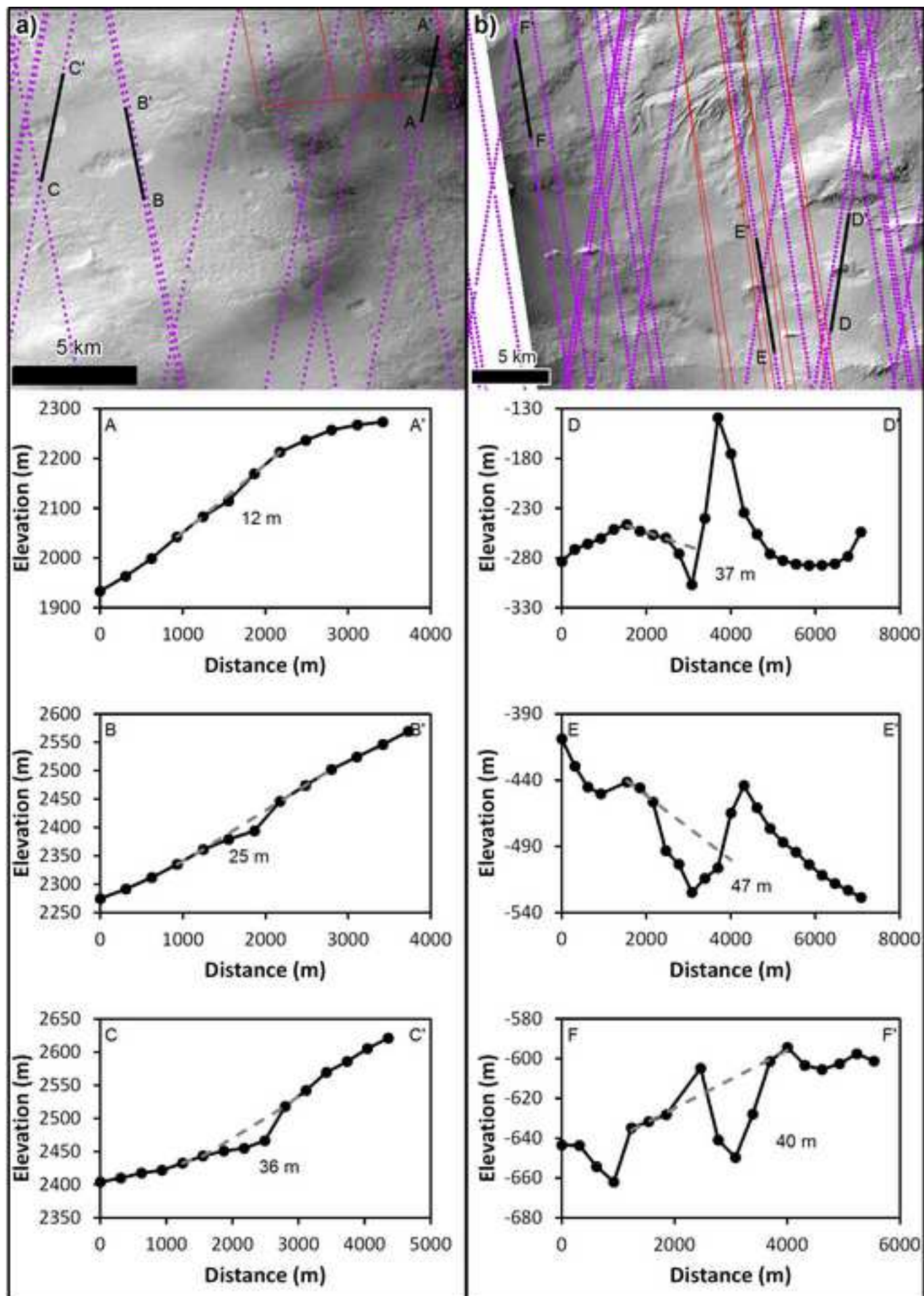




Figure

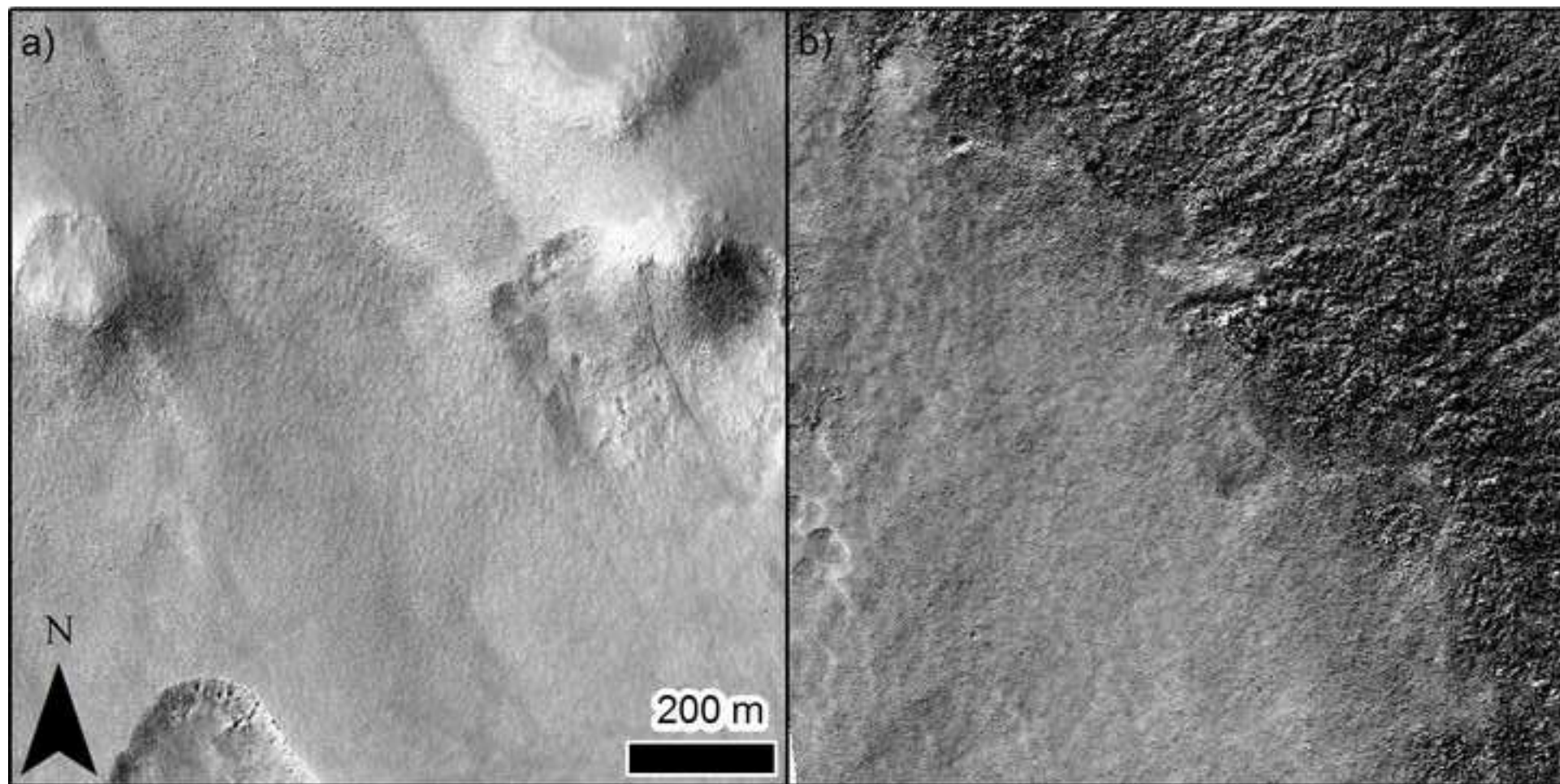


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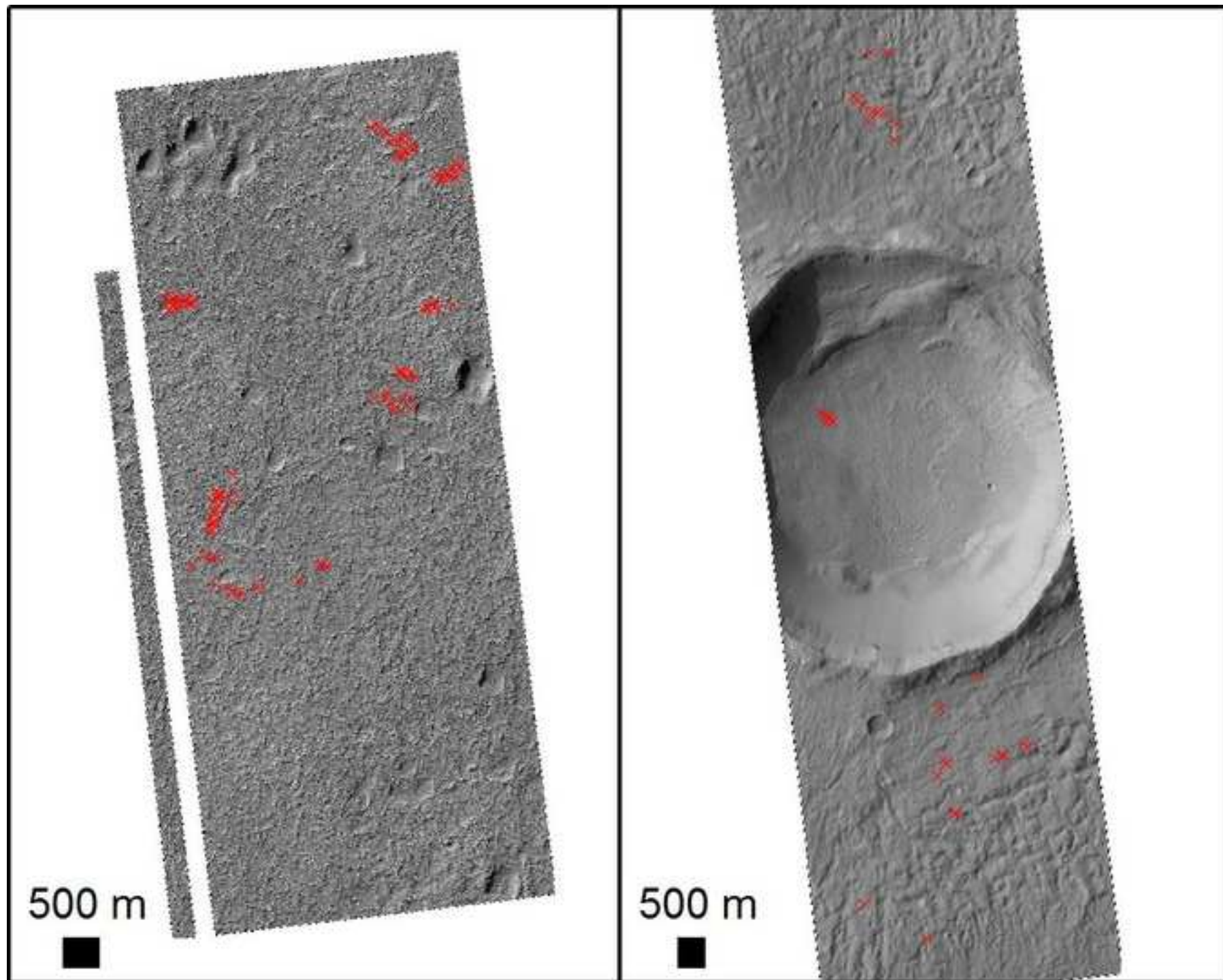




Figure



Figure



**Table 1:** Location and details of sites identified as having Type 1 depressions in this study.<sup>a</sup>

Image #	Location	Site	Image reference	cm/pixel	longitude	latitude	Gullies	Polygons	Unit(s)	Unit Name(s)
1	1		ESP_039392_1450	25	323.816	34.588	x	x	C1	Old crater materials
2	2		PSP_004976_1450	50	322.723	34.797	x	x	C1	Old crater materials
3	3	(a)	ESP_012874_1450	25	322.526	34.869	x	x	C1	Old crater materials
4		(b)	ESP_013019_1450	25	322.525	34.872	x	x	C1	Old crater materials
5	4	(a)	PSP_007033_1445	50	321.183	35.000		x	Nabr (and Nh2 in northernmost 10%, Cr in very SE)	Argyre basin and rim materials
6		(b)	ESP_016197_1445	50	321.184	35.004		x	Nabr (and Nh2 in northernmost 10%, Cr in very SE)	Argyre basin and rim materials
7	5		ESP_040974_1395	25	334.513	40.255	x	x	C1	Old crater materials
8	6		ESP_038521_1345	50	337.943	44.975		x	Cr and Cfs	Old crater materials and Smooth crater floor materials
9	7		PSP_006901_1325	50	327.104	47.078		x	NArb	Argye rim and basin materials
10	8		ESP_034829_1325	50	326.933	47.304	x	x	NArb	Argye rim and basin materials
11	9		ESP_034829_1325	50	326.933	47.304	x	x	NArb	Argye rim and basin materials
12	10		PSP_006993_1320	25	335.384	47.804	x	x	NAb1	Argyre basin and rim materials
13	11		PSP_002457_1310	25	335.305	48.208	x	x	NAb1	Argyre basin and rim materials
14	12		ESP_011911_1310	50	335.371	48.533	x	x	NAb1	Argyre basin and rim materials
15	13		PSP_001349_1310	50	335.336	48.578	x	x	NAb1	Argyre basin and rim materials
16	14		ESP_023925_1305	25	297.495	48.851		x	Nh1 and Hnb	Highlands member 1 and Highlands basins materials
17	15		ESP_011319_1305	50	298.954	49.001		x	Nh1	Highlands member 1
18	16		ESP_039049_1280	25	331.610	51.484	x	x	C2	Young crater materials
19	17		ESP_021960_1280	25	305.499	51.706		x	C1	Old crater materials
20	18		ESP_038640_1275	25	332.262	52.267	x	x	C2	Young crater materials
21	19	(a)	PSP_003711_1275	25	300.895	52.312		x	NAb1, NArb, NAr	Argyre basin member 1, Argye rim and basin materials, Argye rim materials
22		(b)	PSP_005333_1275	25	300.902	52.324		x	NAb1, NArb, NAr	Argyre basin member 1, Argye rim and basin materials, Argye rim materials
23	20	(a)	ESP_032628_1275	25	300.048	52.398		x	NAb1, NArb, NAr	Argyre basin member 1, Argye rim and basin materials, Argye rim materials
24		(b)	ESP_032773_1275	25	300.049	52.399		x	NAb1, NArb, NAr	Argyre basin member 1, Argye rim and basin materials, Argye rim materials
25	21		PSP_003922_1275	25	300.755	52.411	x	x	NAb1, NArb, NAr	Argyre basin member 1, Argye rim and basin materials, Argye rim materials
26	22		PSP_005319_1245	25	324.839	55.273	x	x	NAr	Argyre rim materials
27	23		ESP_013890_1240	50	307.523	55.615		x	NAb1, NAr	Argyre basin and rim materials, Argye rim materials
28	24		PSP_006176_1225	25	323.637	57.130		x	NArb	Argyre rim and basin materials
29	25		PSP_002761_1220	25	317.578	57.610		x	NArb, NAb2, NAb3	Argyre rim and basin materials, Argyre basin member 2, Argyre basin member 3

<sup>a</sup>"x" means the feature is present.

**Table 2:** Location and details of sites identified as having Type 2 depressions in this study.<sup>a</sup>

Image #	Location	Site	Image reference	cm/pixel	longitude	latitude	Gullies	Polygons
1	1	(a)	ESP_023396_1490	50	338.302	30.832	x	
2		(b)	ESP_024319_1490	50	338.300	30.834	x	
3	2	(a)	PSP_008153_1480	50	337.094	31.475	x	
4		(b)	PSP_009155_1480	50	337.095	31.475	x	
5		(c)	ESP_021695_1480	25	337.094	31.457	x	
6		(d)	ESP_022684_1480	50	337.096	31.485	x	
7	3		ESP_020232_1480	50	320.528	31.687	x	
8	4		ESP_017330_1475	50	349.176	31.991	x	
9	5		ESP_025758_1475	50	293.004	32.064		
10	6		ESP_027247_1470	50	321.371	32.249		
11	7	(a)	ESP_022895_1475	25	338.199	32.321	x	
12		(b)	ESP_022262_1475	25	338.199	32.322	x	
13	8	(a)	ESP_039286_1480	25	337.091	31.469	x	
14		(b)	ESP_027075_1475	25	338.194	32.348	x	
15		(c)	ESP_027774_1475	25	338.195	32.350	x	
16		(d)	ESP_038112_1475	25	338.196	32.350	x	
17		(e)	ESP_036345_1475	50	338.196	32.352	x	
18		(f)	ESP_031954_1475	25	338.204	32.354	x	
19		(g)	ESP_035501_1475	25	338.197	32.353	x	
20		(h)	ESP_037057_1475	50	338.198	32.356	x	
21		(i)	ESP_030820_1475	25	338.205	32.357	x	
22		(j)	ESP_032165_1475	25	338.205	32.358	x	
23		(k)	ESP_013836_1475	25	338.193	32.360	x	
24	9		PSP_008364_1475	50	336.325	32.433		
25	10		PSP_007916_1475	50	328.560	32.412		
26	11		ESP_034908_1465	50	327.791	33.121		
27	12	(a)	PSP_006756_1465	25	322.972	33.257		
28		(b)	ESP_023779_1465	25	322.977	33.263		
29	13		ESP_016262_1465	25	347.469	33.263	x	
31	14		ESP_028776_1465	25	343.720	33.324	x	
32	15		ESP_026733_1460	25	315.544	33.524		
33	16		ESP_021734_1460	25	353.240	33.752	x	
34	17		ESP_025466_1460	50	345.292	33.788		
35	18		ESP_034816_1460	50	320.094	33.966		
36	19	(a)	ESP_013098_1455	25	329.129	34.293	x	
37		(b)	PSP_004145_1455	25	329.123	34.305	x	
38	20		PSP_005806_1450	25	341.814	34.792		
39	21		ESP_028645_1450	50	320.647	34.882		
40	22		ESP_026851_1445	25	334.395	35.002		
41	23		ESP_017040_1445	50	347.511	35.017		
42	24		PSP_008114_1445	50	322.404	35.404	x	
43			ESP_017331_1440	50	322.647	35.730	x	
44	25		PSP_007679_1440	50	320.695	35.438		
45	26		PSP_007652_1440	25	338.813	35.540	x	

Image #	Location	Site	Image reference	cm/pixel	longitude	latitude	Gullies	Polygons
46	27		ESP_028552_1440	50	339.485	35.640	x	
48	28	(a)	ESP_022315_1440	25	330.846	35.843	x	
49		(b)	ESP_028038_1440	50	330.859	35.874	x	
50		(c)	ESP_036187_1440	50	330.858	35.875	x	
51		(d)	ESP_030517_1440	25	330.859	35.877	x	
52		(e)	ESP_028315_1440	25	330.860	35.879	x	
53	29	(a)	PSP_007468_1440	25	322.285	35.714	x	
54		(b)	PSP_006822_1440	25	322.285	35.720	x	
55	30		ESP_020166_1440	25	322.988	35.898		
56	31		PSP_008628_1435	50	326.543	35.986		
57	32		ESP_017436_1435	50	335.806	36.075		
58	33		ESP_030083_1435	50	301.948	36.084	x	
59	34		ESP_016501_1430	50	302.683	36.455	x	
60	35		ESP_025704_1430	50	326.490	36.555		
61	36		ESP_017594_1430	50	341.608	36.560	x	
62	37		PSP_010118_1430	50	325.712	36.581		
63	38		ESP_039115_1430	25	325.719	36.583		
64	39		ESP_040948_1430	25	324.416	36.738		
65	40		ESP_034104_1430	50	319.155	36.893		
66	41	(a)	ESP_015959_1425	25	340.227	37.010	x	
67		(b)	ESP_020706_1425	25	340.236	37.020	x	
68		(c)	PSP_007441_1425	50	340.232	37.098	x	
69	42		ESP_031176_1425	50	340.069	37.126	x	
70	43	(a)	PSP_006663_1425	25	343.355	37.034	x	
71		(b)	ESP_011436_1425	25	343.353	37.353	x	
72	44	(a)	ESP_039616_1420	25	329.319	37.535	x	?
73		(b)	ESP_039682_1420	25	329.316	37.524	x	?
74	45	(a)	ESP_025638_1425	50	330.327	37.195	x	
75		(b)	ESP_035264_1420	50	329.452	37.498	x	
76		(c)	ESP_026983_1420	50	329.451	37.516	x	
77		(d)	ESP_034341_1420	50	328.989	37.546	x	
78	46	(a)	ESP_016711_1420	50	329.360	37.610	x	
79		(b)	PSP_007771_1420	50	329.355	37.644	x	
80	47		ESP_013824_1420	25	306.731	37.801	x	
81	48		ESP_028420_1420	50	343.841	37.809		
82	49		PSP_007824_1420	50	322.026	37.895		
83	50		ESP_016078_1415	25	331.163	37.992	x	
84	51		ESP_026377_1415	50	315.180	38.081		
85	52		ESP_019995_1415	50	311.740	38.142		
86	53		ESP_038231_1410	50	330.955	38.513	x	
87	54		ESP_029765_1405	25	343.502	39.119		x
88	55		ESP_039721_1400	25	343.302	39.558	x	
89	56		PSP_008022_1405	50	315.598	39.425	x	
90	57		ESP_016829_1395	50	348.397	40.082		
91	58		ESP_040974_1395	25	334.513	40.255	x	x
92	59		ESP_038785_1390	25	334.041	40.881	x	?

Image #	Location	Site	Image reference	cm/pixel	longitude	latitude	Gullies	Polygons
93	60		ESP_029462_1385	50	336.370	41.136		
94	61	(a)	ESP_029963_1385	25	337.550	41.202	x	
95		(b)	ESP_030596_1385	25	337.554	41.212	x	
96	62		ESP_016211_1380	25	301.066	41.610	x	
97	63		ESP_016038_1370	25	343.722	42.478		
98	64		ESP_027167_1370	50	349.113	42.515		
99	65		ESP_041013_1370	25	349.907	42.657	x	
100	66	(a)	ESP_032086_1370	25	336.126	42.652	x	
101		(b)	ESP_032653_1370	25	336.155	42.658	x	
102	67		ESP_021855_1365	50	290.478	43.200		
103	68		ESP_037084_1360	50	322.576	43.780	x	
104	69		ESP_028514_1360	50	299.475	43.815		
105	70		PSP_004118_1355	25	347.701	44.138	x	
106	71		ESP_036887_1350	50	300.830	44.526		
107	72		ESP_032152_1340	25	335.015	45.473		
108	73		ESP_025071_1335	50	330.711	46.311		
109	74		ESP_034829_1325	50	326.933	47.304	x	
110	75	(a)	ESP_038917_1325	25	333.794	47.311	x	
111		(b)	ESP_029950_1325	25	333.483	47.399	x	
112	76		ESP_015933_1320	50	331.427	47.894		
113	77		ESP_032825_1310	25	320.439	48.617		
114	78	(a)	ESP_033299_1305	50	335.893	49.351		
115		(b)	ESP_024372_1305	50	335.910	49.345		
116	79		ESP_023475_1285	50	343.847	50.947		x
117	80		ESP_013587_1285	25	298.573	51.052		
118	81		AEB_000001_0150	25	300.769	52.203		
119	82	(a)	ESP_012848_1235	25	316.839	56.211		
120		(b)	ESP_012782_1235	25	316.838	56.218		
121	83		ESP_032377_1230	50	314.042	56.867		

<sup>a)</sup>“x” means the feature is present and “?” means uncertain.