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1 **Evidence for Amazonian mid-latitude glaciation on Mars from impact crater**

2 **asymmetry**

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11 **Abstract**

12 We find that craters slopes in the mid-latitudes of Mars have a marked north-south
13 asymmetry, with the pole-facing slopes being shallower. We mapped impact craters in two
14 southern hemisphere sites (Terra Cimmeria and Noachis Terra) and one northern hemisphere
15 site (Acidalia Planitia) and used elevation data from the High Resolution Stereo Camera
16 (HRSC) onboard Mars Express to find the maximum slope of the impact crater's walls in the
17 four cardinal directions. Kreslavsky and Head (2003) using Mars Orbiter Laser Altimeter
18 (MOLA) track data found that, in general, conjugate slopes are shallower in the pole-facing
19 direction, but over a narrower ($\sim 10^\circ$) and more constrained latitude band. They linked the
20 asymmetry to active-layer formation (thaw) at high obliquity. However, Parsons and Nimmo
21 (2009) studied crater asymmetry using MOLA gridded data and found no evidence of a
22 relationship between crater asymmetry and latitude. Our work supports the observations of
23 Kreslavsky and Head (2003), and shows that asymmetry is also found on conjugate crater
24 slopes below the resolution of MOLA, over a wider latitude band than found in their work.
25 We do not systematically find a sudden transition to asymmetric craters with latitude as
26 expected for thaw-related processes, such as solifluction, gelifluction, or gully formation. The
27 formation of gullies should produce the opposite sense of asymmetry to our observations, so
28 cannot explain them despite the mid-latitude location and pole-facing preferences of gullies.
29 We instead link this asymmetry to the deposition of ice-rich crater deposits, where the base of
30 pole-facing slopes receive ten to hundreds of meters of additional net deposition, compared to
31 equator-facing ones over the mid-latitudes. In support of this hypothesis we found that craters
32 in Terra Cimmeria that have deposits on both their floor and pole-facing walls, occur
33 preferentially at the mid-latitudes and have marked positive asymmetry. These deposits were
34 likely laid down during high obliquity excursions ($>45^\circ$) at least 5 My ago and potentially
35 over the whole Amazonian epoch.

36 KEYWORDS: Mars, Surface; Cratering; Mars, climate; Ices

37 **Highlights**

- 38 • Pole-facing slopes are shallower from HRSC elevation between 30 and 50°N/S.
- 39 • The N-S asymmetry is best explained by preferred deposition of ice-rich deposits on
40 the pole-facing slope.
- 41 • These deposits were laid down at high obliquity during the Amazonian.

42 **1. Introduction**

43 The morphology of the surface of Mars is dominated by impact craters, which are continually
44 added to its surface. After emplacement craters are modified by active surface processes and
45 thus if global trends can be observed in crater morphology then information can be obtained
46 about the active processes and therefore past climate (e.g., Craddock et al., 1997; Mangold et
47 al., 2012). Kreslavsky and Head (2003) found using 0.3 km baseline MOLA (Mars Orbiter
48 Laser Altimeter) data that pole-facing slopes are shallower than equator-facing ones over the
49 mid-latitudes (40-50°N and S). They attributed this slope asymmetry to the thawing of
50 ground ice under high obliquity conditions.

51 In contrast Parsons and Nimmo (2009) modeled the expected asymmetry due to long-
52 term viscous creep of ground ice forced by insolation-driven variations in temperatures and
53 found that this produced pole-facing slopes that were steeper than equator-facing ones. To
54 validate their results they measured the slope asymmetry of 120 craters in both hemispheres
55 (diameters of 16-40 km) using MOLA gridded data. This method has potential advantages
56 over the Kreslavsky and Head (2003) one, because conjugate slopes within craters are the
57 same age and on average craters are symmetrical on formation. However, the observations of
58 Parsons and Nimmo (2009) showed no systematic pattern in crater wall slope asymmetry
59 contrary to the predictions of their numerical model and the observations of Kreslavsky and
60 Head (2003). They attribute the discrepancy between their asymmetry measurements and

61 those of Kreslavsky and Head (2003) to either a lack of small craters in their study, or to
62 different slope processes being active in craters compared to those on other types of slopes.

63 The distinction between the different hypotheses proposed by these two groups of
64 authors is important for the following reasons. Firstly, relaxation of crater-form through long-
65 term deformation (Parsons and Nimmo, 2009) strongly implies the presence of tens to
66 hundreds of meters of ice-rich regolith at or very near the surface for periods of 100,000
67 years or more. However, deformation of crater shape through repeated episodes of thaw
68 concentrated on pole-facing crater walls, as described by Kreslavsky et al. (2008), only
69 requires: a) the top few meters of the surface to be ice-rich and b) does not necessarily require
70 this ice to be permanent, just present when warmer conditions occur. These two hypotheses
71 have very different implications for the martian water cycle and the reservoir of water ice
72 over the Amazonian. The first hypothesis implies that a large and shallow cryosphere has
73 been present on Mars for long periods of the Amazonian, whereas the second implies only
74 temporary and superficial water ice, possibly resulting from exchange with the atmosphere.

75 To attempt to resolve these conflicting results we revisit this mid-latitude zone in
76 Terra Cimmera, Noachis Terra and Acidalia Planitia and analyze the slopes within all
77 resolvable craters using HRSC (High Resolution Stereo Camera) data (Fig. 1). The higher
78 resolution (~100 m compared to ~450 m) of this dataset compared to MOLA allows us to
79 study smaller craters. We decided to measure conjugate slopes inside craters so as to assess
80 slopes with the same age, hence same time of exposure to surface processes. This enables us
81 to compare rates of crater wall degradation with orientation and determine if different
82 processes have been acting according to exposure orientation.

83 **2. Methods**

84 All available level 4 HRSC elevation data on ESA's Planetary Science Archive (Scholten et
85 al., 2005) with a resolution of 125 m or better and accompanying orthorectified images were

86 used in the three areas spanning the maximum latitude range possible. The elevation data use
87 the GMM3 Aeroid as a vertical reference (Gwinner et al 2008). Table 1 lists the images and
88 elevation data resolutions for each study area. The elevation data were reprojected into a
89 sinusoidal projection having a central meridian at the center of each study area (155° for
90 Terra Cimmeria, 10° for Noachis Terra and 351° for Acidalia Planitia). The elevation data
91 were resampled to a constant pixel resolution of 75 m/pixel and where there was data overlap
92 the data with higher resolution and/or better quality were used to avoid sampling craters in
93 these areas twice. We chose this resolution as a compromise: to preserve information from
94 the 50 m/pix data and so as not to heavily oversample the 100-125 m/pix data. The crater
95 catalog MA130301GT (Salamuniccar et al., 2011) was used as a basis for mapping of craters
96 down to 0.75 km in diameter. Impact craters visible in the images and hillshade model of the
97 elevation data were digitized as circles in the sinusoidal projection of each study area. Craters
98 that are obviously oblate were excluded from the survey. The center was computed from this
99 circle for each crater and the distance and direction of each elevation pixel from the crater-
100 center was calculated.

101 Errors in the elevation data stem from two sources: firstly the internal elevation
102 uncertainty derived from the stereo-photogrammetric method and secondly the error
103 introduced by superposing adjacent strips. Absolute deviation of the HRSC elevation data
104 from the MOLA spot heights is reported to be on the order of 29 m with a standard deviation
105 of 41 m (Gwinner et al., 2009) and this corresponds well to the magnitude of the noise that
106 we observe in our HRSC data. HRSC level 4 products can have significant shift and rotation
107 between adjacent strips (Dumke et al. 2008). Where our craters intersected with boundaries
108 between HRSC strips we did not find horizontal misalignment greater than 1 pixel. However,
109 we found the average elevation differences between overlapping elevation data strips in the

110 Terra Cimmeria region to be between 0.7 m and 9.3 m with a standard deviation of between
111 15 and 42 m.

112 To account for these uncertainties and the natural variability in crater shape we analyzed
113 the topographic trends in quadrants of the crater, rather than in individual line-profiles. HRSC
114 elevation noise has a normal distribution centered on the ‘real’ elevation value (Gwinner et
115 al., 2009); hence average profiles calculated from the data within crater quadrants are more
116 robust than single line-profiles are to these errors. The data within 1.25 crater diameters of
117 the crater center were extracted for further analysis. These data were divided into quadrants,
118 north-, south-, east- and west-facing. We calculated the worst-case meridional distortion by
119 taking the furthest crater from the projection center at the highest latitude (125 km and 72°S
120 in Noachis Terra) and took the angular difference between true north and the map-projected
121 north from the map. At worst the meridional distortion introduced by the projection system
122 was $\sim 5.7^\circ$ from the true north direction at the edges of the study regions. So in the worst case
123 6% of the pixels (5.7° span of a 90° segment) included to calculate the average profile could
124 be incorrectly assigned. Only if these data were consistently and systematically different from
125 their neighbors (i.e. greater than the noise, ~ 40 m) would they shift the mean profile, hence
126 we considered this error as negligible. For each of these quadrants the mean elevation and its
127 standard error were calculated in 75 m distance bins (Fig. 2). The standard error on the mean
128 elevation for each bin was on average less than 5 m, hence sometimes smaller than the points
129 in Fig. 2. Throughout we use the term “standard error” to refer to the likelihood that our
130 calculated mean is a true representation of the population mean, i.e. sd / \sqrt{n} , where sd is the
131 sample standard deviation and n is the number of samples.

132 This mean profile was used to calculate the maximum crater slope on the crater wall, as
133 follows. Firstly a weighted linear model was fitted to each point and its two nearest neighbors
134 and the gradient and standard error of the gradient were recorded. The weights were

135 proportional to the inverse of the standard error on the mean elevation for those points.
 136 Secondly the maximum positive gradient value was taken as the maximum crater slope on the
 137 crater wall and its associated standard error was recorded. The slope calculated is therefore an
 138 estimate of the maximum slope at length-scales of 150 m. The crater wall was defined as the
 139 interval between the position of maximum curvature and the rim (Fig. 2). The rim was
 140 assumed to be the highest point on the profile or at the distance given by the circle-radius if
 141 no maximum could be found before the end of the profile.

142 The asymmetry, “A”, of the slopes was calculated similarly to Parsons and Nimmo
 143 (2009), but considering equator- and pole-facing slopes rather than north- and south-facing
 144 ones:

$$145 \quad A = S_{eq} - S_p / S_{avg}, \quad (1)$$

146 where S_{eq} is the equator-facing slope, S_p the pole-facing and S_{avg} the average of the N-, S-, E-
 147 and W-facing slopes. Using this system, an equator-facing slope which is steeper than a pole-
 148 facing slope leads to a positive value of A in both hemispheres. The error in A (σ_A) is
 149 estimated using propagation of errors, as follows:

$$150 \quad \sigma_A = (\sqrt{(\sigma_{seq}^2 + \sigma_{sp}^2)}) / S_{avg} \quad (2)$$

151 where σ_{seq} is the standard error for the equator-facing slope and σ_{sp} is the standard error
 152 estimated for the pole-facing slope, both derived from the fitting of the weighted linear model
 153 as described above. The estimates of error on the mean (σ_{Amn}) of asymmetry per latitude bin
 154 presented in Table 2 were derived by propagating the individual errors of A (σ_A) as follows:

$$155 \quad \sigma_{Amn} = \frac{\sqrt{\sum_{i=0}^n (\sigma_{Ai}^2 + \sigma_{Ai+1}^2 + \sigma_{Ai+2}^2 + \dots)}}{n} \quad (3)$$

156 To provide an estimate of regional slope the median value of the topography was taken
 157 between 1.4 and 1.5 crater radii for each quadrant. The difference in elevation was then taken
 158 between the equator- and pole-facing, and the W- and E-facing quadrants and normalized by

159 the crater's radius. For the analysis of the asymmetry data, craters superposed on strong
160 regional slopes were excluded. A strong regional slope was defined as a normalized
161 difference in elevation of greater than 5%.

162 **3. Results**

163 In Terra Cimmeria we mapped 567 craters between 0.75 – 39 km diameter, 664 craters
164 between 0.75 – 68 km diameter in Noachis Terra and in Acidalia Planum 687 craters between
165 0.75 - 46 km diameter. The latitudinal evolution of the maximum slope of crater walls for
166 each region is shown in Fig. 3a. The propagated error on the mean for the slope
167 measurements is less than 0.003 (m/m) for all latitude bins with more than 20 craters over all
168 study zones in Fig. 3a (Table 2). In general agreement with previous global studies using
169 MOLA data (Kreslavsky and Head, 2003), we also find that the slopes of crater walls
170 decrease towards the high latitudes (Fig. 3a). This decrease is gradual in Acidalia Planum and
171 Terra Cimmeria, but abrupt in Noachis Terra. Median slope values dip below 0.18 in Noachis
172 Terra at 35° latitude, whereas values below 0.18 are not found until 50° latitude in Acidalia
173 Planum and Terra Cimmeria. At latitudes greater than 55° craters in all regions have slopes of
174 ~0.18. In contrast, below 30° of latitude, slopes stretch between ~0.3 and ~0.5, which are
175 typical of fresh craters (e.g., Mangold et al., 2012).

176 Figure 3b shows how the asymmetry of crater walls changes with latitude. Each region
177 has a different pattern, but each has marked positive asymmetry (steeper equator-facing
178 slopes) in the mid-latitudes. The propagated error on the mean for the asymmetry
179 measurements is on average 0.01 (and always less than 0.03) for all latitude bins with more
180 than 20 craters for all study zones in Fig. 3b (Table 2). There is a strong scattering of the data
181 for all three regions studied. This effect is expected because of the natural variability of
182 impact crater shape from differences in formation processes and bedrock. As craters at
183 equatorial latitudes ($\leq 22.5^\circ$) have high slopes typical of weakly degraded fresh craters, we

184 have used these regions to estimate the natural variation in asymmetry. Taking all the craters
185 at these latitudes ($n=162$), the median value (-0.02) has a standard error of asymmetry of
186 ± 0.03 , corresponding to a 95% confidence limit of ± 0.06 (calculated by multiplying the
187 standard error by 1.96, the position of 95% area under the normal distribution). Hence, a
188 median asymmetry value $>|0.06|$ is a significant signal (when the number of craters sampled
189 is large, see Table 2) and thus linked to crater degradation, rather than natural variability. The
190 fact that asymmetry is systematically positive for most mid-latitude regions is consistent with
191 this interpretation.

192 A more detailed inspection shows that, in Terra Cimmeria, the mean and median
193 asymmetry changes smoothly, with positive asymmetry between 50° and 30° , which peaks at
194 45° and a small negative asymmetry at 55° . This asymmetry variation is similar to that
195 predicted by relaxation of ~ 100 m of creeping permafrost (Parsons and Nimmo, 2009), but
196 has the opposite sign, as discussed in more detail in Section 4. In Noachis Terra craters have
197 positive mean and median asymmetry at 65° , 50° and $40-25^\circ$ and marked negative
198 asymmetry at $15-10^\circ$ and 60° and a small negative asymmetry at 55° . The negative anomalies
199 at $55-60^\circ$ in Noachis Terra and Terra Cimmeria will be discussed further in Section 4.3.
200 Acidalia Planum has positive median and mean asymmetry from 50° to 40° and negative
201 values at 10° . Absolute mean and median values are lower than for the two previous regions,
202 and only slightly above 0.06 at latitudes from 50 to 40° , suggesting that this region is less
203 affected by the process creating asymmetry.

204 A comparison between Figs. 3a and 3b shows that the asymmetry is an intrinsic
205 parameter that does not depend on the slope value. For example, between 30° and 50° in
206 Terra Cimmeria, there is continuous positive asymmetry and the slopes range from ~ 0.25 to
207 0.4. Figure 4 shows how the asymmetry is expressed for different sizes of craters between the
208 latitudes of 27.5 to 42.5° where the asymmetry is high for two of the regions (Fig. 3b).

209 Craters between 1.5 and 8 km have the most marked asymmetry ($\gg 0.1$) for the two southern
210 hemisphere regions. Craters at 0.5-1.0 km and 4-16 km in Acidalia Planum have weakly
211 positive asymmetry, but unlike the other two regions this latitude zone does not have strong
212 asymmetry in Fig. 3b, so we will not discuss this region further in this context. Craters larger
213 than 8 km and smaller than 1 km in Terra Cimmeria have no significant asymmetry. All
214 craters in Noachis Terra have positive asymmetry, with the least asymmetric craters being in
215 the 0.5-1.5 km diameter range.

216 The variation of asymmetry with depth to diameter ratio ($d:D$) for the three study zones
217 is shown in Fig. 5 in the latitude zone 27.5 to 42.5° (as for Fig. 4). Craters with $d:D > 0.1$ in
218 Acidalia Planum have weakly positive mean and median asymmetry and the other craters
219 have no significant values of asymmetry. In both Terra Cimmeria and Noachis Terra craters
220 with $d:D > 0.05$ have asymmetry >0.1 and craters with $d:D < 0.025$ are less asymmetric. The
221 main difference between the two regions is for craters with $d:D$ range of 0.025-0.05: craters
222 in Terra Cimmeria have no significant asymmetry whereas those in Noachis Terra have a
223 mean and median asymmetry between 0.1 and 0.2.

224 **4. Implications and discussion**

225 **4.1 Comparison with previous work**

226 We compared our results to the asymmetry predicted by the modeling of viscous creep
227 performed by Parsons and Nimmo (2009). They modeled the creep of an ice-rich layer of 3
228 different thicknesses (50, 100 and 150 m, dotted curves in Fig. 3b) in a 30 km diameter crater
229 using varying obliquity (Laskar et al., 2004) over the last 100 My. For the temperature-wave
230 to affect the depth over which deformation by ice creep occurs there must be significant
231 differences in year-average insolation between the equator- and pole-facing slopes. Year-
232 average insolation is greatest on equator-facing slopes, and at higher obliquities the
233 magnitude of the difference decreases. The negative asymmetries found by Parsons and

234 Nimmo (2009) result from deformation with an average obliquity of 34° . However, we find
235 significant positive asymmetry, rather than negative in the latitude range predicted by their
236 model in all of our study regions (Fig. 3b). Despite the sign being reversed it is important to
237 note that the magnitude of the asymmetry observed approaches that predicted by their model
238 for a deforming layer 150 m thick in Terra Cimmeria and Noachis Terra. This observation
239 will be discussed in more detail in Section 4.3.

240 In contrast, the sense of the asymmetry and its latitudinal location from our study are in
241 agreement with the results of Kreslavsky and Head (2003) (green or grey bars, Fig. 3), but
242 there is a broader zone of asymmetry in our study areas (Fig. 3b). This may be explained by
243 the different methods used to measure asymmetry. Kreslavsky and Head (2003) considered
244 the distribution of all north- and south-facing slopes within $\sim 14 \times 14$ km cells, whereas we
245 considered conjugate craters slopes at a range of different length-scales (from ~ 1 -150 km).
246 Kreslavsky and Head (2003) explained their observations by invoking the melt or the
247 deformation of an active layer (Kreslavsky et al., 2008) on pole-facing slopes at high
248 obliquity. Although year-average insolation is still greatest on equator-facing slopes at high
249 obliquities, at obliquities above $\sim 30^\circ$ (depending on the slope inclination) day-average
250 insolation is greater on the pole-facing slope (e.g., Costard et al., 2002).

251 In summary, considering the processes presented in these two models the asymmetry we
252 have measured can only come about if temperatures are greater on the pole-facing, compared
253 to the equator-facing slope, in the mid-latitudes. Ice-creep as modeled by Parsons and Nimmo
254 (2009) produces steeper pole-facing slopes at any *average* obliquity up to 50° and the process
255 of thaw/active layer formation as proposed by Kreslavsky et al. (2008) only produces steeper
256 equator-facing slopes under high obliquity excursions. Hence, our observations can only be
257 explained by periods of high obliquity if thaw is the agent of degradation.

258 **4.2 Timeframe of asymmetry development**

259 Craters from 2 to 8 km are those which display the most asymmetry (Fig. 4). The large
260 majority of these craters formed >100 My ago. The frequency of craters in this diameter bin
261 in any of these three areas is of the timescale of ~100 My (after Hartmann and Neukum,
262 2001). This means, that, statistically, there is no more than one 2.83-4 km crater younger than
263 100 My. Hence, the timing of the asymmetry development of these craters should be of the
264 order of 100 My. The depth to diameter ratio ($d:D$) can be used a rough proxy for the
265 degradation state of the crater (e.g. Robbins and Hynek, 2012), hence craters with large $d:D$
266 values are ‘fresh’ and those with small $d:D$ values are ‘degraded’. The craters with the
267 highest $d:D > 0.1$ (‘freshest’) and the lowest $d:D < 0.025$ (‘degraded’) in Terra Cimmeria and
268 Noachis Terra have less pronounced positive asymmetry than those with an intermediate $d:D$
269 (Fig. 5). If the development of asymmetry happened prior to the Amazonian then we would
270 expect only ‘degraded’ craters to show the asymmetry, conversely if it was very recent then
271 we would expect craters with all degradation states to exhibit asymmetry. Neither is the case,
272 so it is likely that the asymmetry was developed during the Amazonian.

273 **4.3 Ice deposition as an agent of asymmetry development**

274 Our asymmetry observations agree with those of Kreslavsky and Head (2003) and Kreslavsky
275 et al. (2008) and these authors propose that the asymmetry of these craters is explained by
276 thaw processes. However, we have also observed that many of our craters contain deposits
277 (Fig. 6), whose form and distribution could also explain the asymmetry. In this section and
278 Section 4.4 we further explore the development of asymmetry by deposition alone and in
279 Section 4.5 go on to explore the plausibility of the other previously proposed mechanisms.

280 In the deposition model pole-facing slopes are a focus for deposition of water ice from the
281 atmosphere and equator-facing slopes either remain ice-free, or collect less ice. For this to
282 produce asymmetry ice must be thicker at the bottom of the slope than at the top. According

283 to the calculations of Parsons and Nimmo (2009) for a 30 km diameter crater 50-150 m of
284 topographic difference is needed to produce our observed magnitude of asymmetry. From our
285 actual asymmetry observations we can make an independent estimate of the thickness of
286 material needed to be deposited, as follows. For any given crater, we can approximate the
287 slope of the ‘pristine’ (i.e. pre-deposition) crater wall by using the slope of the equator-facing
288 crater wall (S_{eq}) and approximate the length of the pristine wall (L_w) by using the equator-
289 facing distance from the maximal concavity to the rim (Fig. 7). We can then simply calculate
290 the maximum thickness of material (Th) as follows:

$$291 \quad Th = L_w \times (S_{eq} - S_p) \quad (4)$$

292 For the 357 craters in Terra Cimmeria and Noachis Terra between 27.5°S and 42.5°S with an
293 asymmetry ≥ 0.2 , this gives an average of the maximum Th estimate of 122 m with the first
294 and third quartiles being 22 m and 150 m respectively. This is similar to the 50-150 m
295 estimate of Parsons and Nimmo (2009) despite our craters having a wide range of diameters.

296 There are two putative ice-rich deposits, which show a similar latitudinal distribution to
297 the zones of positive asymmetry: firstly the latitude dependent mantle (LDM) and secondly
298 ice-deposits within craters, often termed Concentric Crater Fill (CFF).

299 To test whether these deposits were responsible for the asymmetry we undertook a survey
300 of all Context Camera images (CTX) at ~ 6 m/pix in the Terra Cimmeria study region. We
301 found CTX images were the only reliable way of identifying LDM, CFF or other ice deposits
302 at the regional scale. We did not perform the same survey in Acidalia Planitia or Noachis
303 Terra because good quality CTX images were not present at all latitudes within these areas at
304 the time of writing. We used the criteria of Head et al. (2010) to identify ice deposits,
305 including the presence of elongate parallel striate, arcuate ridges, sublimation pits and
306 troughs: some examples of the deposits are shown in Fig. 6. We divided ice deposits into

307 three types according to their distribution within the crater: floor deposits, deposits on the
308 pole-facing wall and deposits on the equator-facing wall.

309 Figure 8 shows that there are very clear trends in ice-deposits with latitude in Terra
310 Cimmeria. Equatorward of 32° we did not find ice deposits in any crater and polewards of
311 38° there are no craters without ice-deposits, with the exception of two fresh craters. At
312 latitudes around 35° the most common deposits are found on pole-facing walls only, then
313 moving polewards these grade into deposits being most common on both the floor and pole-
314 facing walls at 42° . Finally at 55° almost all craters have floor, pole- and equator-facing
315 deposits. Craters with positive asymmetry (where pole-facing slopes are shallower than
316 equator-facing ones) occur at latitudes where deposits are predominantly located on both
317 pole-facing walls and on crater floors (Fig. 8). The link is substantiated by the observation
318 that the 72 craters with both pole-facing and floor deposits have the highest asymmetry
319 amongst all of the other deposit-configurations with an average asymmetry of 0.25, compared
320 to 0.07 for the 110 craters without any deposits. The negative asymmetry expressed at 55°
321 corresponds to an area where crater floors and pole- and equator-facing walls all have
322 deposits. Negative asymmetry is also found at the same latitude in Noachis Terra and from
323 available images, the deposits also cover the whole crater. This zone of negative anomalies
324 corresponds to a region with a higher than average thermal inertia (Putzig et al., 2005),
325 interpreted as “Rocks, bedrock, duricrust and polar ice”. This provides additional evidence
326 that the deposits covering these craters could be both extensive and ice-rich.

327 **4.4 Link with previously mapped ice deposits**

328 The distribution of the dissected mantle or LDM (Mustard et al., 2001) coincides with
329 zones where we observe positive asymmetry in all three study areas (Fig. 3). In Terra
330 Cimmeria we observed LDM “pasted-on” to pole-facing slopes in 36% of craters and that
331 craters with pole-facing deposits are concentrated in zones of higher positive asymmetry

332 (Fig. 8). However, thickness estimates for the LDM are of the order of tens of meters (e.g.,
333 Mustard et al., 2001; Willmes et al., 2012) and in places up to 40 m (Zanetti et al., 2010). The
334 most recent estimates of the age of the mantle from Kostama et al. (2006) range from 5 to 0.1
335 My. Up to six distinct stratigraphic layers were found in areas of degradation by Schon et al.
336 (2009), who link these layers to excursions to high obliquity in the last 5 My. Hence, the
337 surface age is younger than the estimated age of asymmetry development, as outlined in
338 Section 4.2. Together the age and thickness of this deposit argue against its dominant role in
339 developing asymmetry,

340 The zones of positive asymmetry also coincide with mapped CFF ice deposits within
341 craters (Fig. 3; Dickson et al., 2012), which are estimated to have thicknesses of up to 1 km
342 (Dickson et al., 2010). Such deposits have been previously linked to positive asymmetry for
343 individual craters in both the northern (Kreslavsky and Head, 2006) and southern hemisphere
344 (Head et al., 2008). Flow directions estimated for the CFF-type fills are predominantly
345 polewards, indicating an accumulation zone on the pole-facing slope (Fig. 6A; Dickson et al.,
346 2012). Levy et al. (2009, 2010) found that LDM superposes CFF in the northern hemisphere
347 and is not deformed in the same way, therefore postdates CFF formation and deformation.
348 Levy et al. (2010) estimate the age of CFF in the northern hemisphere to be older than 70 My
349 with ages potentially going back to 1 Ga. This is consistent with our estimate for the timing
350 of the asymmetry development (as outlined in Section 4.2). These estimates of thickness and
351 age are consistent with our observations, even though we accept the large margin for error on
352 the age estimates.

353 Accepting ice-deposits within craters as a plausible candidate, we now examine the
354 processes of developing asymmetry. For positive asymmetry to be developed, the slope of the
355 pole-facing slope must be reduced compared to the equator-facing one. This cannot be done
356 by simply placing a blanket of material of the same thickness across the pole-facing wall.

357 Hence, on the pole-facing slope there must be either 1) less deposition at the top of the slope,
358 or 2) removal of the deposits at the top of the slope (by sublimation), or 3) flow downhill of
359 the deposits previously located at the top of the slope. Option 3 could be a possibility because
360 some of our craters contain pole-facing glacier like forms (GLFs) as mapped by Souness et
361 al. (2012) and our study areas cross the region of viscous flow features mapped by Milliken
362 et al. (2003). Dickson et al. (2012) found that not all of their mapped ice-deposits have
363 characteristics indicating flow (only ~50% in Noachis Terra and Acidalia Planitia according
364 to their Fig. 3). Our own observations confirm those of Dickson et al. (2012); we only found
365 10 (out of 124 with floor deposits) that exhibited flow features in Terra Cimmeria (example
366 in Fig. 6C). Hence, flow downhill of ice-deposits cannot be a universal mechanism for
367 asymmetry development.

368 From our observations we cannot differentiate between uneven deposition on the pole-
369 facing crater wall, as opposed to deposition everywhere and removal at the crater rim. The
370 summits of crater rims are exposed to insolation and wind from two orientations hence form
371 both a hostile environment for ice deposition, and a favored location for ice-removal.

372 A deposition model explains the lack of correspondence between the latitudinal trends in
373 crater wall slopes and their asymmetry (Fig.3) without having to invoke two different
374 processes. The asymmetry is explained solely by differences in deposition with orientation
375 and the slope trend by the overall amount of deposition; hence craters at higher latitude have
376 a greater amount of infill (so lower slopes), but can still have uneven deposition (so are still
377 asymmetric). The greatest asymmetry is observed in craters between 1.5 and 8 km (Fig. 4)
378 and this can easily be explained by the deposition model: smaller craters tend to be
379 completely infilled and larger craters only protect limited amount of ice near their crater wall
380 (Fig. 6D), rather than across their whole crater floor, hence neither exhibit strong asymmetry.
381 The depth to diameter ratios in Fig. 5 support this by indicating that asymmetric craters range

382 from “fresh”, hence practically unfilled (deposits on the walls) to moderately filled (d:D
383 >0.025).

384 The deposition model can also provide an explanation as to why there are marked
385 negative excursions at 55-60° in Terra Cimmeria and Noachis Terra: from image data we find
386 these craters are completely covered with deposits (including the rims), hence these craters
387 are subject to universal deposition and may have undergone viscous relaxation to produce
388 asymmetry as proposed by Parsons and Nimmo (2009).

389 We have shown that to develop the crater slope asymmetry, whereby pole-facing slopes
390 are shallower than equator-facing ones in the mid-latitudes, tens to hundreds of meters of
391 additional net deposition is required at the base of the pole-facing slope compared to the
392 equator-facing one (Section 4.3). This implies that pole-facing slopes in the mid-latitudes
393 have been good environments for deposition and preservation of ice-rich deposits in the
394 Amazonian period. From our observations we cannot differentiate between a single episode
395 of deposition followed by preservation and multiple cycles of deposition and preservation.

396 Net deposition relies on deposition exceeding removal by sublimation or more rarely
397 melting. Climate models suggest that deposition of ice should occur at obliquity > 45°
398 (Forget et al., 2006), with such obliquities occurring in clusters 1-2 My apart, during the
399 time-period preceding 5.5 My ago (Laskar et al, 2002; 2004). Ice may preferentially be
400 deposited on pole-facing slopes at high obliquity, because they have lower day-average
401 insolation than equator-facing ones under high obliquity conditions, despite these slopes also
402 experiencing the highest day-average temperatures in summer (Kreslavsky et al. 2008). The
403 ice deposited during these high obliquity periods must also survive the intervening time. The
404 lower year-average temperatures on pole-facing slopes at any obliquity compared to equator-
405 facing ones helps to slow the sublimation and preserve deposits there as observed in Greg
406 crater (Hartmann et al., 2013).

407 **4.5 Other candidate processes for asymmetry development**

408 Kreslavsky and Head (2003) and Kreslavsky et al. (2008) favored thaw-related processes to
409 generate asymmetry, including: a) creep, in the form of active layer creep (solifluction and/or
410 gelifluction) or b) overland flow, or debris flow associated with gullies. Kreslavsky et al.
411 (2008) argue that the asymmetry and lack of steep slopes at high latitudes must be accounted
412 for by thaw-processes rather than any other process for the following two reasons: 1) The
413 transition from preservation of steep slopes to shallower slopes occurs over a very narrow
414 band and thus must be related to a threshold process, such as melting. However, we find that
415 this rapid transition is only observed in Noachis Terra (Fig. 3b), so this argument cannot be
416 used in favor of thaw-related processes. 2) Steep slopes are preserved at the equator despite
417 the evidence for glacial activity; hence flowing-ice cannot explain slope-lowering. However,
418 this only applies a) if the deposits are no longer present and b) if the flowing ice did not
419 experience basal melting (so non-erosive). We have found that in areas with marked positive
420 asymmetry there are still ice-deposits present, but there is not always evidence of flow.
421 Hence, this argument does not preclude that cold-based, or non-moving ice-deposits could
422 cause asymmetry, rather than thaw-processes.

423 Active layer creep only occurs within the top few meters of the ground and only when
424 temperatures are above zero, and on Earth horizontal displacement rates are on the order of
425 10cm/yr or less, with annual thaw (e.g., Alexander and Price, 1980). On Mars, thaw would be
426 less common and the distance from the rim to base of the slope is on average 1.3 km (range:
427 0.2-11.6 km). Hence, simply moving material the required distance would take 130 Earth-like
428 thaw cycles, without considering the fact that the deposits can be 22-150 m thick. This seems
429 unlikely, but only modeling of depth-limited creep could reveal if this amount of mass
430 transfer was plausible over realistic timescales for the martian environment. Unfortunately
431 the lobes and terraces which would indicate gelifluction/solifluction processes, as seen

432 elsewhere on Mars (Gallagher et al., 2011; Johnsson et al., 2012) are on the decameter scale
433 so would not necessarily be identifiable on CTX images. Hence, the role of active-layer creep
434 in generating asymmetry cannot be completely ruled out.

435 Gullies are thought to be the result of overland flow or debris flow (e.g., Costard et al.
436 2002; Heldmann et al., 2005). Gullies occur in our study regions and are predominantly pole-
437 facing in accordance with other global-scale studies (e.g., Balme et al., 2006; Kneissl et al.,
438 2010). Gullies are found only on steep slopes ($>18^\circ$ or 0.32 m/m, Conway et al., 2012). This
439 observation could be explained by gullies causing the steeper slopes - removal of material
440 near the top of the slope tends to increase, rather than decrease the maximum slope angle
441 (e.g., Ballantyne and Benn, 1994). This action would lead to negative slope asymmetry. If
442 gullies require steep slopes to form (and do not steepen the slopes) then asymmetries
443 developed on crater walls below 0.32 slope angle cannot be explained by gully-forming
444 process. In either case, gullies cannot be the dominant process causing asymmetry. If gullies
445 are associated with degradation of the thicker pole-facing ice-deposits, as suggested by
446 Berman et al. (2005), then gullies could be an explanation for the scatter in our data in the
447 mid-latitudes.

448 **5. Conclusions**

449 We find an asymmetry in conjugate crater wall slopes for mid-latitude regions whereby pole-
450 facing crater walls are shallower than equator-facing ones over a wide band ($30-50^\circ$) for our
451 three study regions. Although the asymmetry that we observe has the same magnitude as the
452 creep of a hundreds of meters thick ice-rich layer (Parsons and Nimmo, 2009), it has the
453 opposite sense. Our work confirms and extends the global asymmetry observations of
454 Kreslavsky and Head (2003) made using MOLA track data, with our data showing that
455 conjugate crater slopes below the resolution of MOLA are also asymmetric, and this
456 asymmetry is expressed over a wider latitude band than found in their work. These authors

457 suggest that asymmetry is related to thaw processes, such as solifluction, gelifluction or
458 gully-formation. However, we do not observe a threshold latitude of onset for the asymmetry
459 as expected for thaw-processes. In addition, gully-formation acts to produce negative
460 asymmetry, hence cannot explain the observations. Therefore, we propose another
461 mechanism to produce asymmetry: the differential deposition of ice. In this model, ice-rich
462 material is preferentially deposited at the base of the pole-facing crater wall under high
463 obliquity periods during the Amazonian. To produce the observed asymmetry tens to
464 hundreds of meters of additional net deposition is required on the pole-facing slope compared
465 to the equator-facing one. This model is supported by our observation in Terra Cimmeria that
466 the most positively asymmetric craters contain deposits on their floors or pole-facing wall.
467 Our observations suggest that these deposits are likely to have formed throughout the
468 Amazonian and are more likely to be similar to those previously described as Concentric
469 Crater Fill (CFF; e.g., Dickson et al., 2012), rather than the thinner surficial latitude
470 dependent mantle (LDM; e.g., Mustard et al. 2001).

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591 **7. Tables**

592 Table 1: HRSC image numbers used for each study area^a

Study area	Image IDs
Acidalia	H1465_0000* ,H3231_0000* , H1498_0000* , H1476_0000, H1249_0000, H1205_0000, H1260_0000, H1216_0000, H3253_0000 ^{\$} , H5350_0000* ,H5368_0000* ,
Noachis	H0430_0000, H1899_0000** , H2258_0000, H2247_0000, H0397_0000, H2225_0000, H2280_0000* ,
Cimmeria	H2066_0000, H2055_0000, H0280_0001, H0293_0000* , H0228_0000, H0241_0000* , H2612_0000* , H2579_0000* , H2590_0001** , H2634_0000**

593 ^aUnless noted as follows data are at 75 m/pix, otherwise: ^{\$} data at 50 m/pix, * data at

594 100 m/pix, ** data at 125m/pix. The order of the images denotes the order in which they

595 were stitched, with the first of the list taking priority.

596

597 Table 2: Summary statistics for crater asymmetry, slope, diameter and depth to diameter ratio by latitude zone and study area^a

Statistic	Area	Latitude												
		10	15	20	25	30	35	40	45	50	55	60	65	70
Count	Acidalia	9	30	37	51	107	120	51	39	16	3	1	0	0
	Noachis	8	32	29	64	59	59	45	42	65	42	27	21	25
	Cimmeria	0	0	17	39	62	99	92	63	31	30	0	0	0
Median	Acidalia	0.103	0.057	0.060	-0.079	-0.009	0.013	-0.119	-0.118	-0.158	-0.204	0.017	NA	NA
	Noachis	-0.106	-0.124	-0.083	0.056	0.192	0.267	0.098	0.029	0.107	0.000	-0.247	0.132	0.021
	Cimmeria	NA	NA	0.051	-0.077	0.075	0.113	0.221	0.272	0.156	-0.077	NA	NA	NA
Mean	Acidalia	0.146	0.031	0.055	-0.038	-0.009	-0.005	-0.081	-0.130	-0.122	-0.003	0.017	NA	NA
	Noachis	-0.161	-0.154	-0.028	0.084	0.159	0.216	0.065	0.019	0.091	-0.142	-0.292	0.191	0.058
	Cimmeria	NA	NA	-0.033	-0.056	0.080	0.131	0.232	0.280	0.305	-0.082	NA	NA	NA
Standard Deviation	Acidalia	0.423	0.482	0.306	0.516	0.411	0.412	0.523	0.599	0.472	0.399	NA	NA	NA
	Noachis	0.248	0.425	0.236	0.400	0.341	0.421	0.613	0.435	0.511	0.551	0.449	0.445	0.384
	Cimmeria	NA	NA	0.204	0.281	0.556	0.452	0.365	0.463	0.540	0.342	NA	NA	NA
Propagated Error	Acidalia	0.022	0.022	0.030	0.033	0.015	0.015	0.020	0.026	0.078	0.093	0.032	NA	NA
	Noachis	0.038	0.028	0.019	0.014	0.010	0.011	0.016	0.017	0.013	0.016	0.022	0.019	0.017
	Cimmeria	NA	NA	0.018	0.019	0.015	0.014	0.012	0.013	0.024	0.026	NA	NA	NA
Count	Acidalia	10	50	67	72	141	188	87	49	18	4	1	0	0
	Noachis	9	43	38	88	72	75	64	52	80	59	33	22	27
	Cimmeria	0	0	32	58	85	136	112	73	36	34	0	0	0
Median	Acidalia	0.266	0.290	0.313	0.263	0.295	0.204	0.236	0.152	0.090	0.182	0.211	NA	NA
	Noachis	0.439	0.282	0.294	0.365	0.270	0.139	0.091	0.121	0.121	0.126	0.151	0.114	0.147
	Cimmeria	NA	NA	0.481	0.391	0.290	0.266	0.215	0.175	0.149	0.152	NA	NA	NA
Mean	Acidalia	0.269	0.299	0.320	0.265	0.277	0.221	0.263	0.219	0.158	0.203	0.211	NA	NA
	Noachis	0.411	0.322	0.330	0.386	0.302	0.177	0.125	0.140	0.154	0.137	0.163	0.125	0.169
	Cimmeria	NA	NA	0.461	0.379	0.314	0.272	0.235	0.191	0.185	0.152	NA	NA	NA
Standard	Acidalia	0.162	0.125	0.166	0.113	0.127	0.119	0.140	0.155	0.150	0.127	NA	NA	NA

Deviation	Noachis	0.175	0.143	0.156	0.156	0.160	0.125	0.089	0.092	0.097	0.078	0.090	0.055	0.063
	Cimmeria	NA	NA	0.120	0.164	0.181	0.127	0.110	0.094	0.117	0.061	NA	NA	NA
Propagated Error	Acidalia	0.002	0.003	0.002	0.002	0.001	0.001	0.001	0.002	0.002	0.005	0.003	NA	NA
	Noachis	0.005	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Median	Cimmeria	NA	NA	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	NA	NA	NA
	Acidalia	2.93	4.91	4.69	3.23	3.41	1.91	2.03	2.33	3.98	4.76	3.15	NA	NA
Mean	Noachis	2.85	2.91	3.04	3.11	1.88	1.43	1.95	2.14	2.03	2.33	4.65	2.70	2.55
	Cimmeria	NA	NA	2.70	2.03	2.18	2.10	2.66	4.39	6.34	6.62	NA	NA	NA
Diameter (km)	Acidalia	2.95	7.73	10.75	8.48	7.70	5.99	3.07	3.72	4.91	25.19	3.15	NA	NA
	Noachis	7.39	8.44	5.02	6.12	4.76	2.82	5.28	6.13	3.59	8.29	6.79	3.34	4.02
Standard Deviation	Cimmeria	NA	NA	10.26	7.39	3.98	5.84	6.56	9.72	14.75	13.21	NA	NA	NA
	Acidalia	1.34	9.29	17.33	15.57	10.96	10.24	2.59	3.50	4.17	36.39	NA	NA	NA
Median	Noachis	8.16	14.89	4.46	10.21	6.10	3.48	9.47	12.05	5.41	22.10	8.58	2.28	3.09
	Cimmeria	NA	NA	16.21	15.48	4.79	9.45	10.80	10.51	15.52	12.60	NA	NA	NA
Mean	Acidalia	0.0965	0.0620	0.0657	0.0589	0.0605	0.0594	0.0643	0.0400	0.0146	0.0326	0.0751	NA	NA
	Noachis	0.0940	0.0648	0.0754	0.0905	0.0707	0.0384	0.0257	0.0259	0.0310	0.0234	0.0316	0.0272	0.0375
Depth:Diameter	Cimmeria	NA	NA	0.0972	0.0822	0.0544	0.0566	0.0484	0.0300	0.0268	0.0243	NA	NA	NA
	Acidalia	0.0805	0.0680	0.0685	0.0625	0.0661	0.0603	0.0662	0.0490	0.0314	0.0461	0.0751	NA	NA
Standard Deviation	Noachis	0.0822	0.0695	0.0758	0.0828	0.0712	0.0408	0.0260	0.0281	0.0346	0.0274	0.0325	0.0283	0.0380
	Cimmeria	NA	NA	0.0983	0.0877	0.0672	0.0609	0.0512	0.0324	0.0307	0.0266	NA	NA	NA
Mean	Acidalia	0.0473	0.0329	0.0364	0.0309	0.0383	0.0341	0.0325	0.0391	0.0346	0.0383	NA	NA	NA
	Noachis	0.0515	0.0295	0.0307	0.0351	0.0328	0.0211	0.0104	0.0131	0.0188	0.0153	0.0149	0.0129	0.0141
Standard Deviation	Cimmeria	NA	NA	0.0551	0.0444	0.0434	0.0340	0.0265	0.0149	0.0213	0.0099	NA	NA	NA

598 ^a including the statistics and sample numbers for the boxplots in Fig. 3. The sample numbers are different between the slope and asymmetry plots

599 because craters with a significant regional slope were excluded from the asymmetry plots, but not the slope plots. The depth and depth:diameter

600 entries have the same number of samples as the asymmetry entries. NA means “not applicable” because there are no craters in that latitude bin.

601 **8. Figure Captions**

602 Figure 1. Study sites. “A” = Acidalia Planum, “C” = Terra Cimmeria and “N” = Noachis
603 Terra. The outlines represent the outlines of the stitched HRSC elevation data.

604

605 Figure 2. Top: plan view of example craters in Terra Cimmeria and bottom corresponding
606 average crater profiles for pole-facing (south-facing) crater slopes. On the left is an example
607 simple crater (35.920°S, 153.841°E) and on the right an example complex crater (27.315°S,
608 157.427°E). For the maps: HRSC images are overlain on a color-stretch of the HRSC
609 elevation data (in online version; red is high and blue is low elevation). The crater center is
610 marked as a dot, solid lines delimit the quadrants used to extract the profile data (at 1.5 crater
611 radii) and dashed lines are the initial crater rim approximation. For the profiles: grey points
612 are the raw data points from the whole quadrant, black points are the average profile and
613 those that lie at distances less than the crater radius are filled. The standard error of each
614 elevation point is given as vertical bars (often within the point). The black line is the straight
615 line connecting the crater’s center (positioned vertically at the measured profile minimum to
616 ignore the central peak) to the rim. The ‘x’ marks the horizontal distance to the maximum
617 slope measurement and the ‘*’ shows the position of maximum curvature (where the distance
618 from the straight line and average profile is greatest). The simple crater from the profile on
619 the left has a maximum slope of 0.33 and curvature of 0.03. The complex crater from the
620 profile on the right has a maximum slope of 0.31 and curvature of 0.16. The Curvature is
621 defined as the maximum distance from the straight line to the average profile normalized by
622 rim-to-floor height.

623

624 Figure 3. Boxplots of (a) the variation of maximum crater slope with latitude and (b) crater
625 wall asymmetry in the three study regions. Note the latitude scale is absolute, so for Acidalia

626 they represent northern latitudes and for the other two sites, southern latitudes. The thick bar
627 across each box is the mean value and the thin bar the median value, the extent of the box
628 delimits the interquartile range, the whiskers indicate the range, while the points are outliers -
629 values which are further than 1.5 interquartile ranges from the quartiles. Sample numbers for
630 these plots are given in Table 2. The boxes are placed on the center of their latitude range.
631 The bars in the panel between the plots represent the latitudinal distribution of: in dark grey
632 (yellow online) = the distribution of crater ice fill as mapped by Dickson et al. (2012), in
633 black (red online) = the boundary between the rough and smooth terrains mapped by
634 Kreslavsky and Head (2000), in white (blue online) zones with dissected mantle noted by
635 Mustard et al. (2001) and in grey (green online) = zones of asymmetry noted by Kreslavsky
636 and Head (2003), “+” meaning the asymmetry was positive and “-” that it was negative. The
637 dotted lines on (b) show the expected asymmetry of craters after 100 My of deformation of a
638 150 m (dash-dot, blue online), 100 m (dotted, red online) and 50 m (dashed, black) thick
639 layer with 40% dust as calculated by Parsons and Nimmo (2009). The grey zone delimits
640 $A = \pm 0.06$ outside which asymmetry values are significant.

641

642 Figure 4. Asymmetry “A” against crater diameter for in the region between 27.5 and 42.5°.
643 Sample numbers are given below the boxes. The thick bar across each box is the mean value
644 and the thin bar the median value, the extent of the box delimits the interquartile range, the
645 whiskers indicate the range, while the points are outliers - values which are further than 1.5
646 interquartile ranges from the quartiles. The grey zone delimits $A = \pm 0.06$ outside which
647 asymmetry values are significant. The intervals are closed on the right (i.e. 1.5-2 indicates
648 $1.5 < D \leq 2$).

649

650 Figure 5. Asymmetry “A” against crater depth:diameter for in the region between 27.5 and
651 42.5°. Sample numbers are given below the boxes. The thick bar across each box is the mean
652 value and the thin bar the median value, the extent of the box delimits the interquartile range,
653 the whiskers indicate the range, while the points are outliers - values which are further than
654 1.5 interquartile ranges from the quartiles. The grey zone delimits $A = \pm 0.06$ outside which
655 asymmetry values are significant. The intervals are closed on the right (i.e. $0.05 < d:D \leq 0.075$
656 indicates $0.05 < d:D \leq 0.075$).

657

658 Figure 6. Examples of positively asymmetric infilled craters, all images are oriented with the
659 pole towards the bottom of the image and the equator towards the top (arrowheads point
660 north) and all scale bars are 1 km. A: Crater at 40.14°S, 156.34°E with an asymmetry of 0.47
661 in Terra Cimmeria, showing evidence of flow of material away from the pole-facing wall.
662 CTX image: P15_006894_1417. B: Crater at 43.44°S, 156.43°E with an asymmetry of 1.14
663 in Terra Cimmeria, showing no evidence of flow, but asymmetric deposition. CTX image:
664 P17_007751_1349. C: Crater at 47.52°N, 8.68°W with asymmetry of 0.21 in Acidalia
665 Planitia with classic Concentric Crater Fill (CFF), this deposit continues up onto the pole-
666 facing crater wall and it absent from the equator-facing wall. The equator-facing wall also
667 hosts a suite of small gully-like landforms. CTX image: B21_017646_2281. D: Crater at
668 31.16°S, 12.92°E in with asymmetry of 0.09 in Noachis Terra. In this case the infill shows no
669 evidence of being ice-rich, but deposition of material at the base of the pole-facing wall
670 (indicated by arrows) has caused the crater to be positively asymmetric. CTX image:
671 P17_007743_1482. CTX images courtesy of NASA/JPL-Caltech/MSSS.

672

673 Figure 7: Diagram to illustrate the calculation of thickness of deposition (Th) required to
674 produce observed asymmetries (Eq. 4). S_p is the slope of the pole-facing wall, S_{eq} is the slope

675 of the equator-facing wall and L_w is the length of the equator-facing wall. If we assume that
676 S_{eq} is a reasonable minimum estimate of the slope of the pre-deposition crater wall, and L_w a
677 reasonable estimate of that wall's length, we can project S_{eq} downwards from the rim of the
678 pole-facing wall over a distance L_w , to estimate the additional thickness of deposition (Th) on
679 the pole-facing wall.

680

681 Figure 8: A map of craters with ice-rich deposits in the Terra Cimmeria study area aligned
682 with a copy of Fig. 3b: a boxplot showing the variation of crater asymmetry with latitude.

683 The different symbols on the map refer to different locations within the crater which host ice-
684 deposits, as indicated in the legend. Where the crater deposits are 'unknown', this means that
685 either, there was no CTX image available, the CTX image contained noise or cloud, or there
686 was too much shadow to clearly see the crater walls. The boxplot is a simplified version of
687 Fig. 3b where the thick bar across each box is the mean value with the extent of the box
688 delimiting the interquartile range.

Figure 1 (colour)
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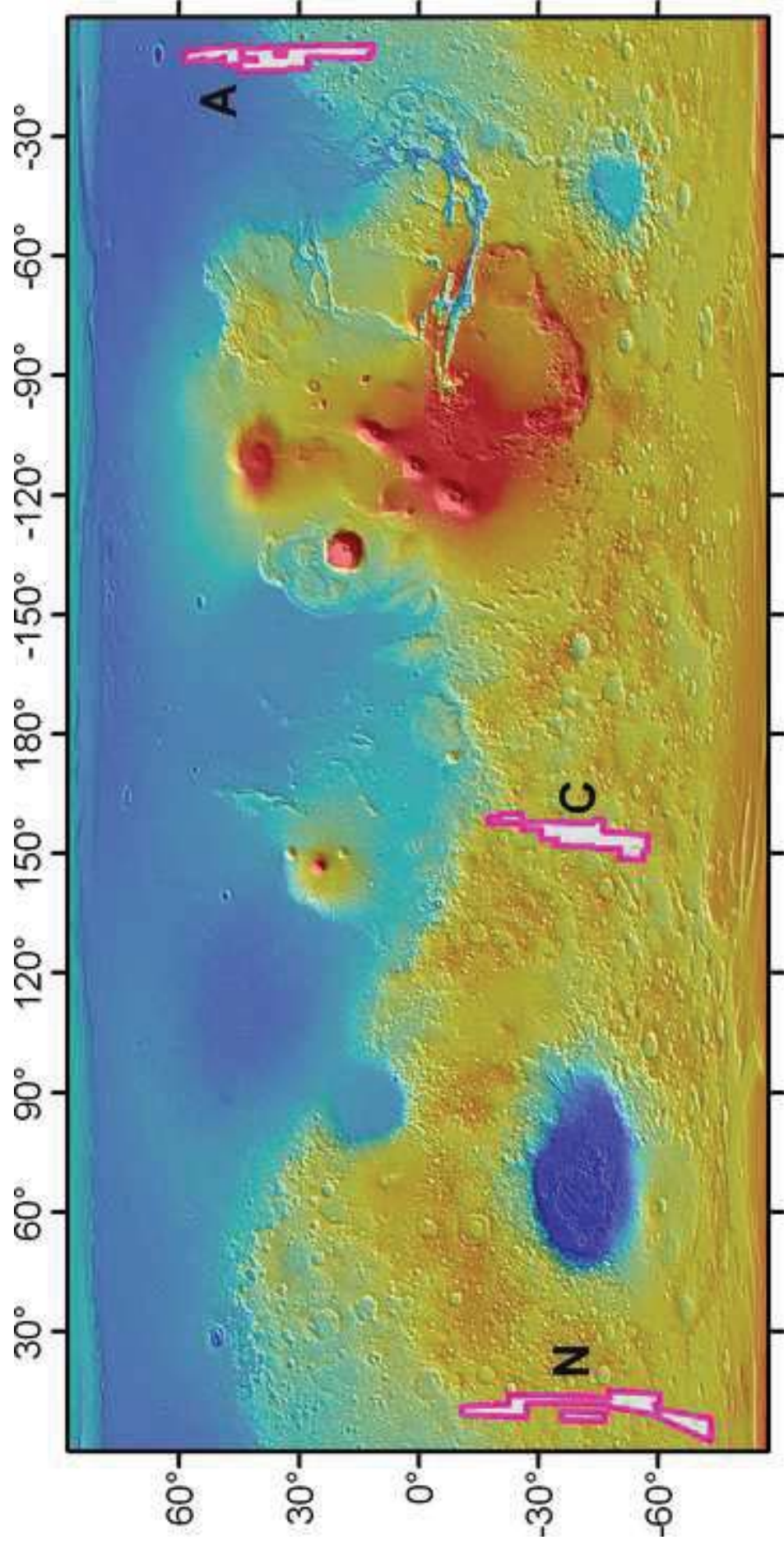


Figure 1
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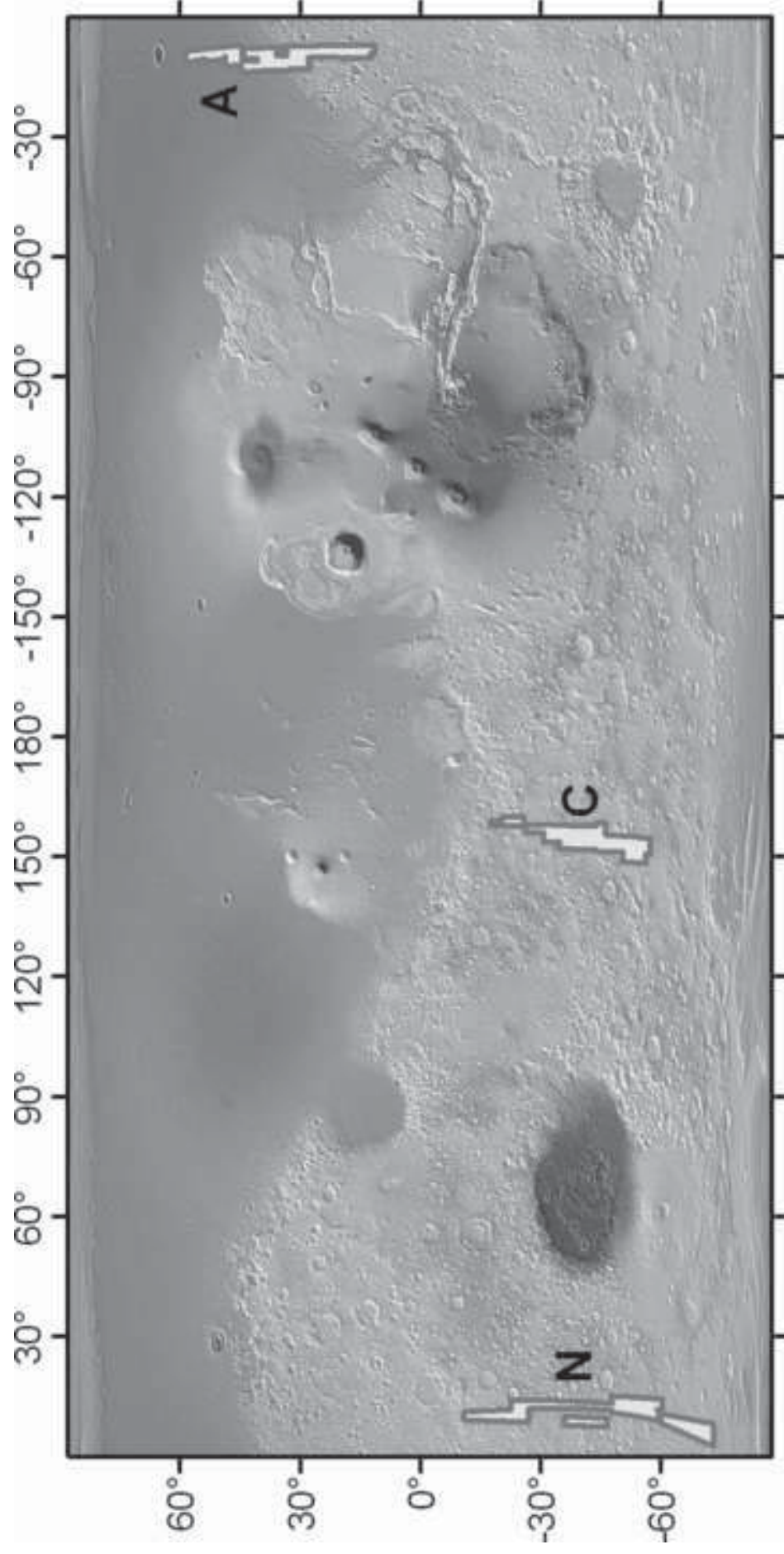


Figure 2 (colour)
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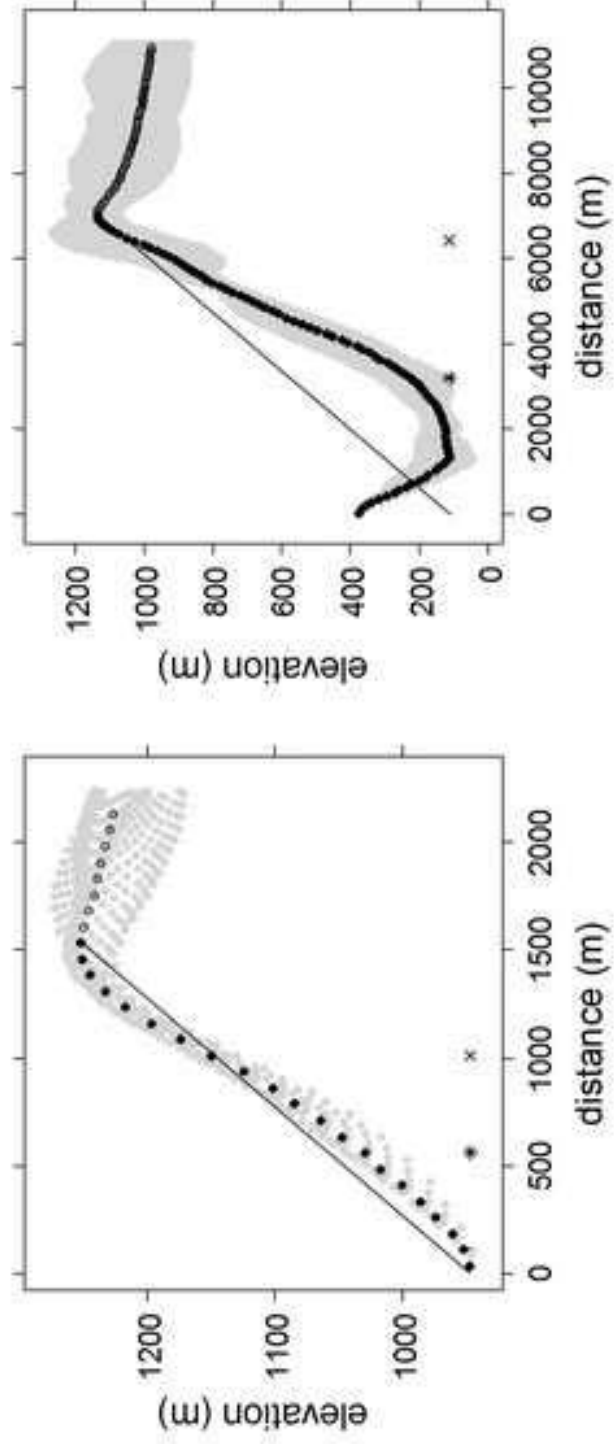
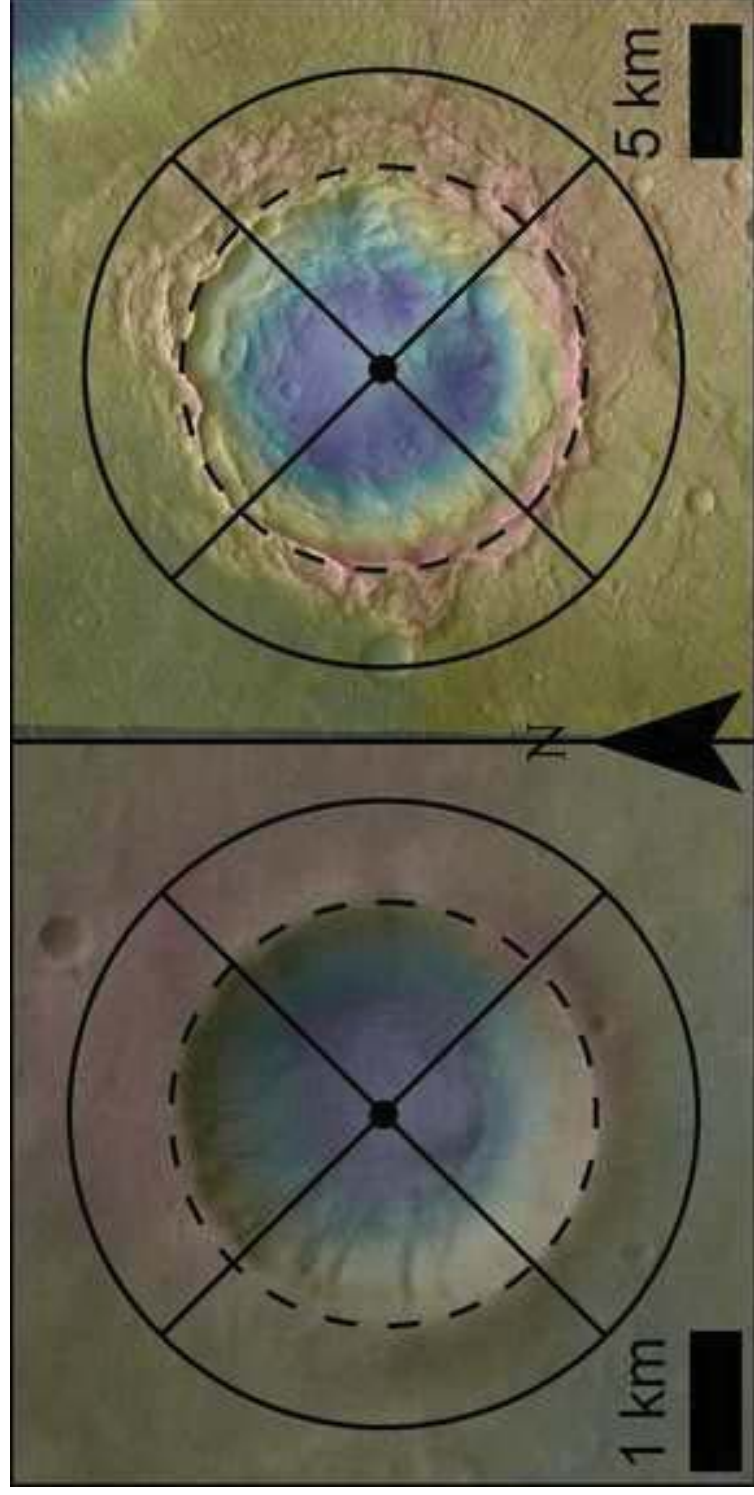


Figure 2
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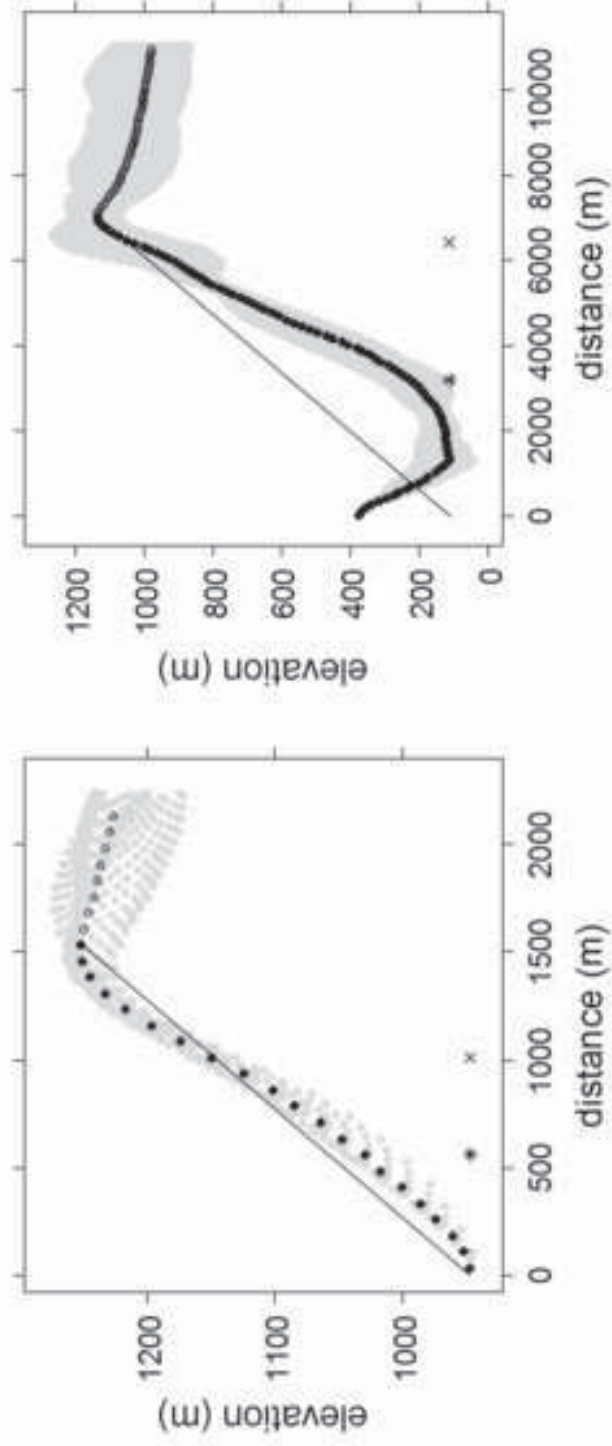
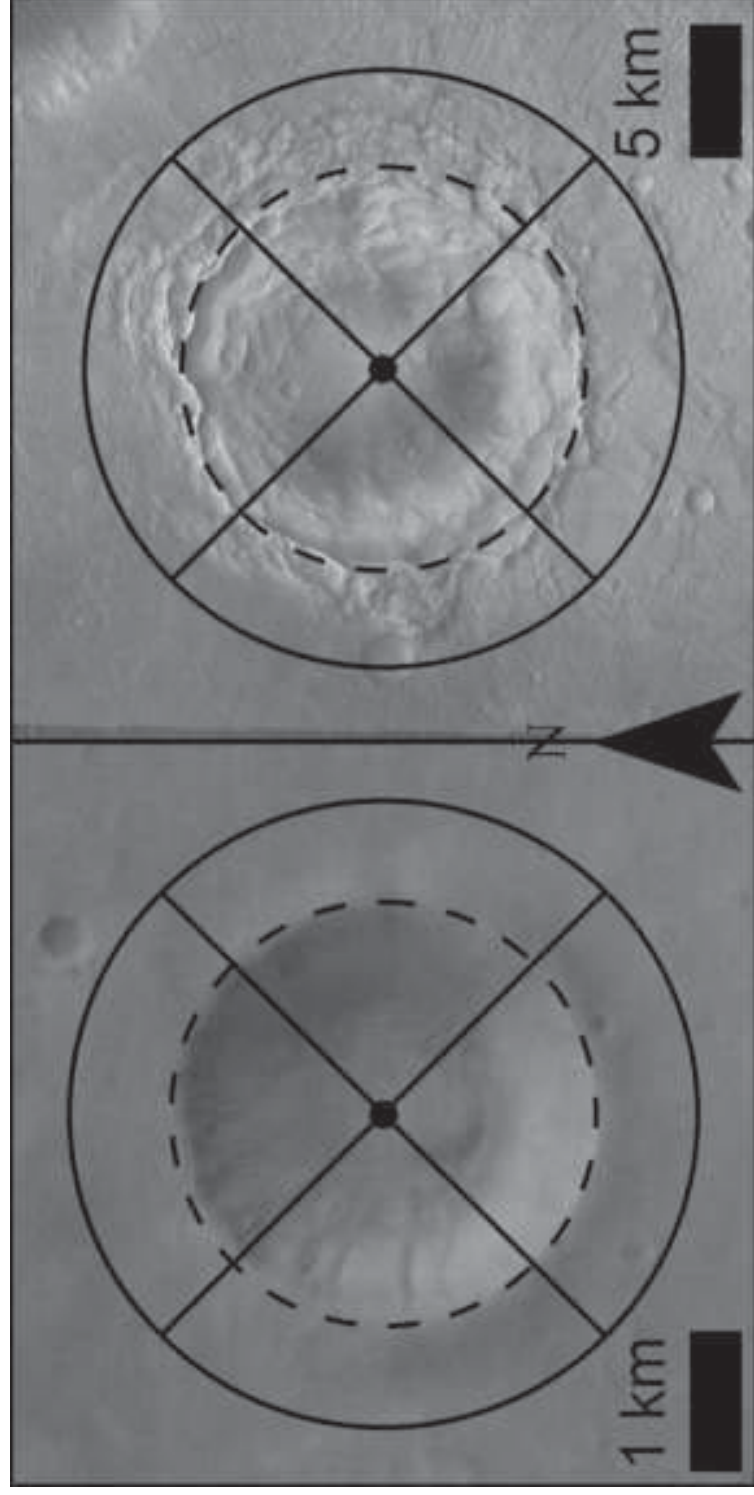


Figure 3 (colour)

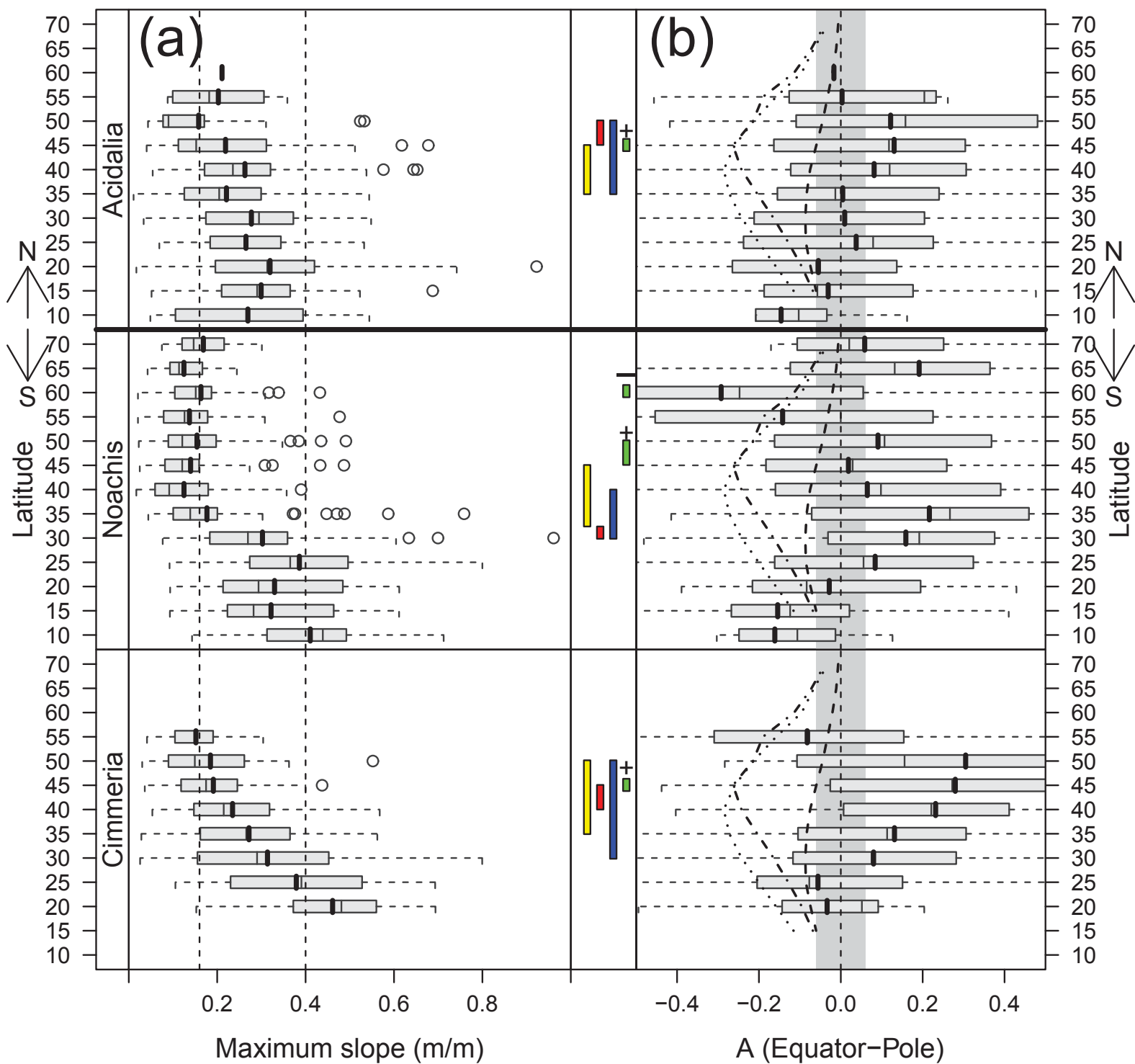


Figure 3

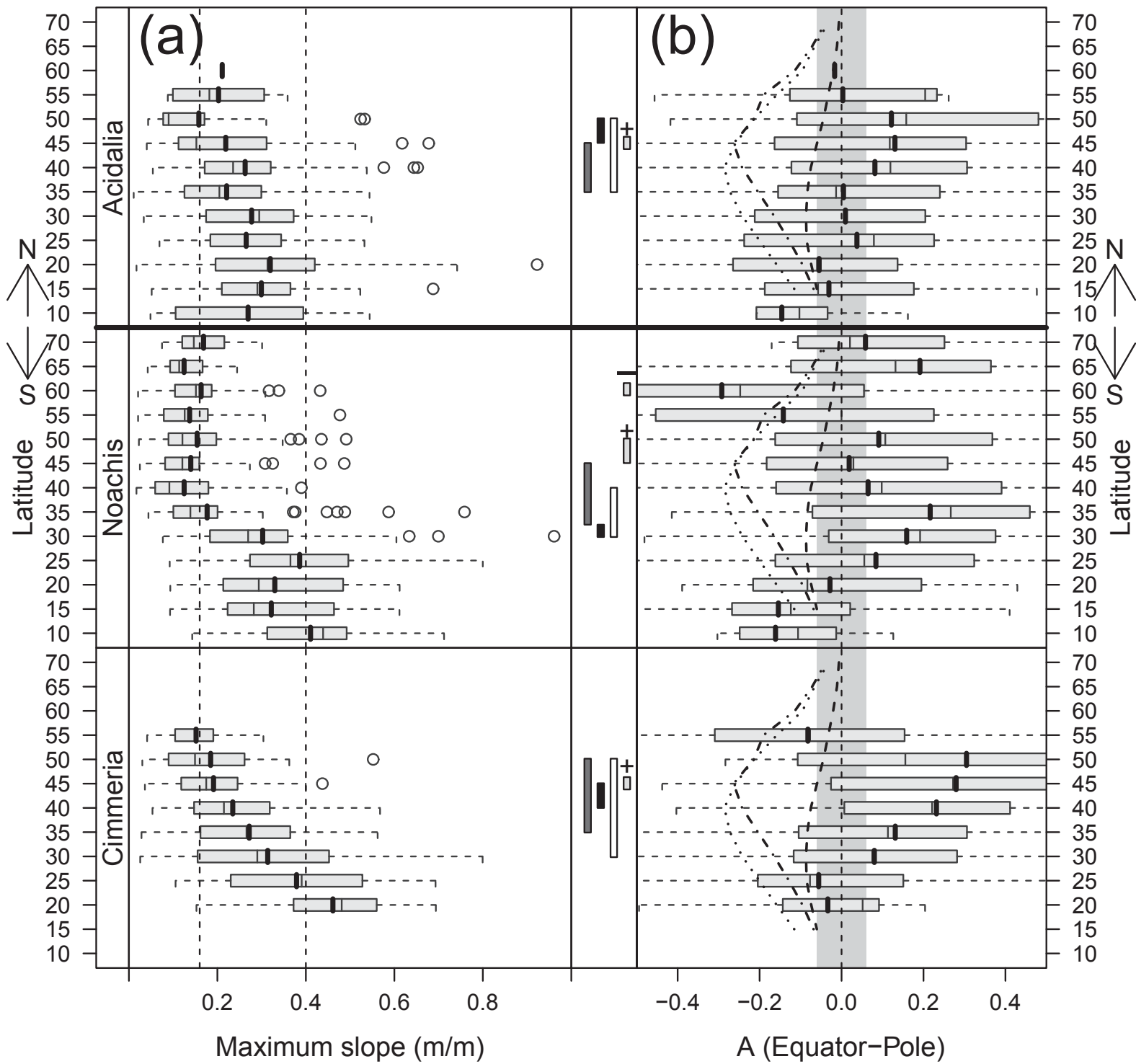


Figure 4

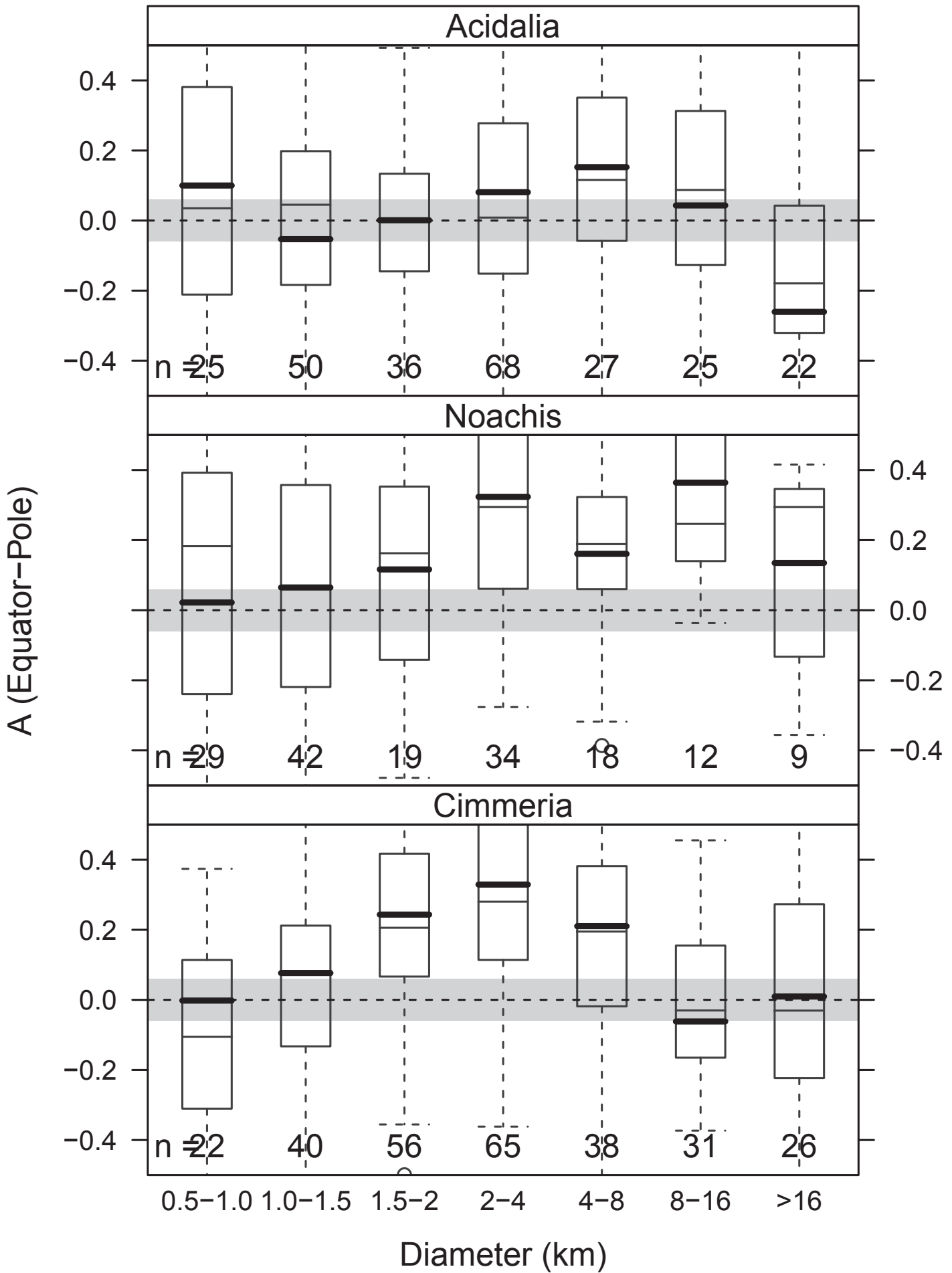


Figure 5

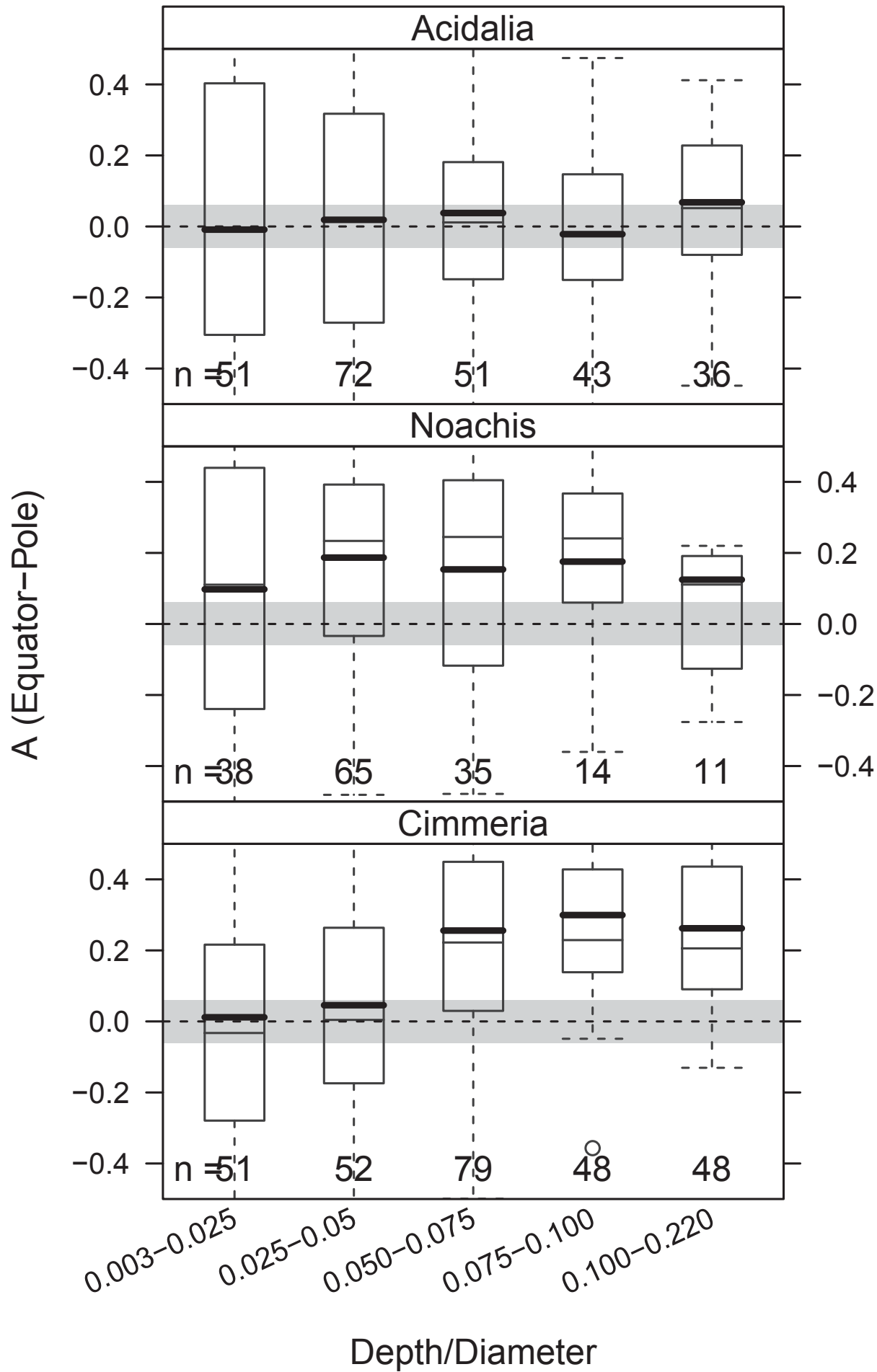


Figure 6
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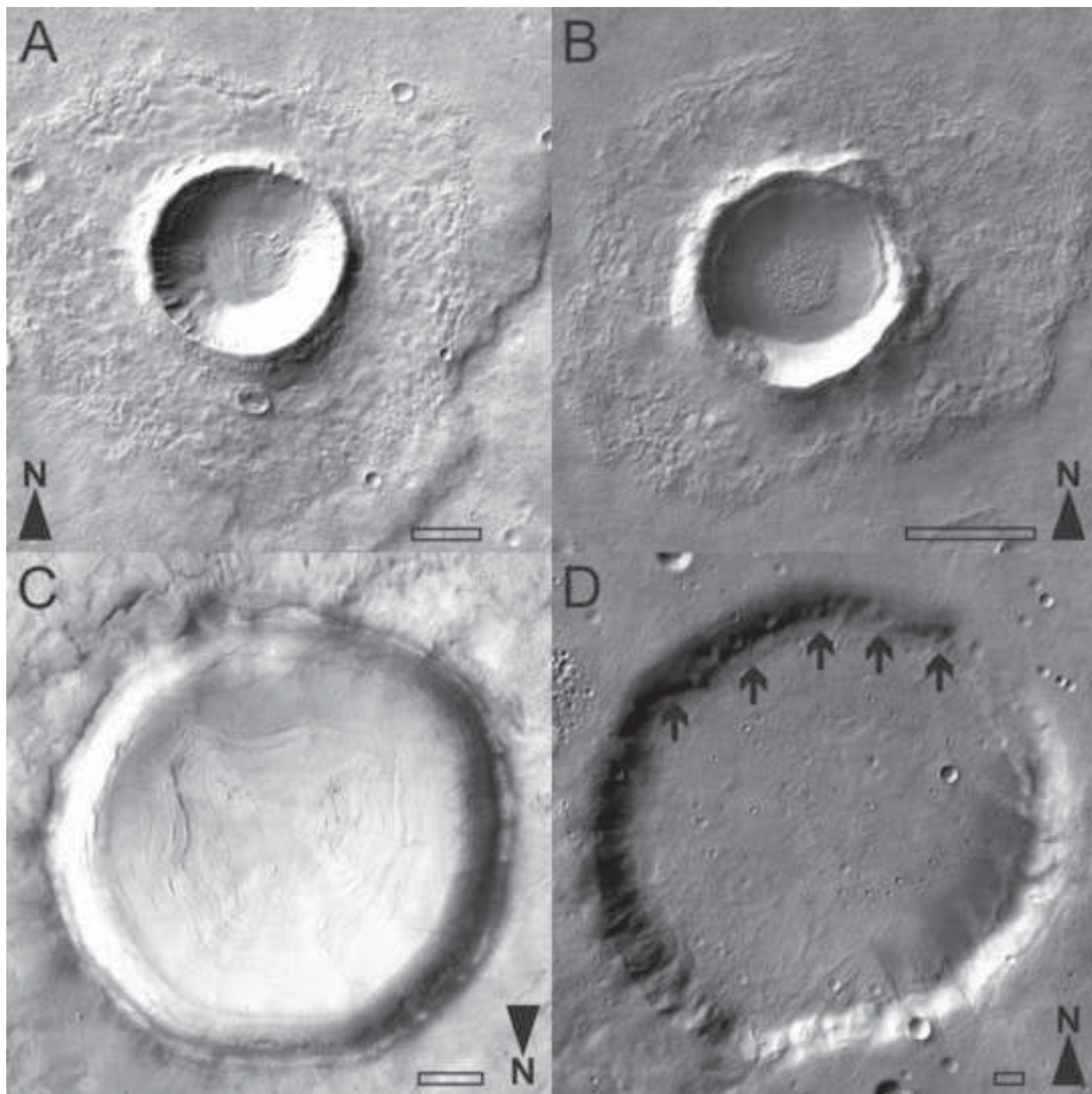


Figure 7

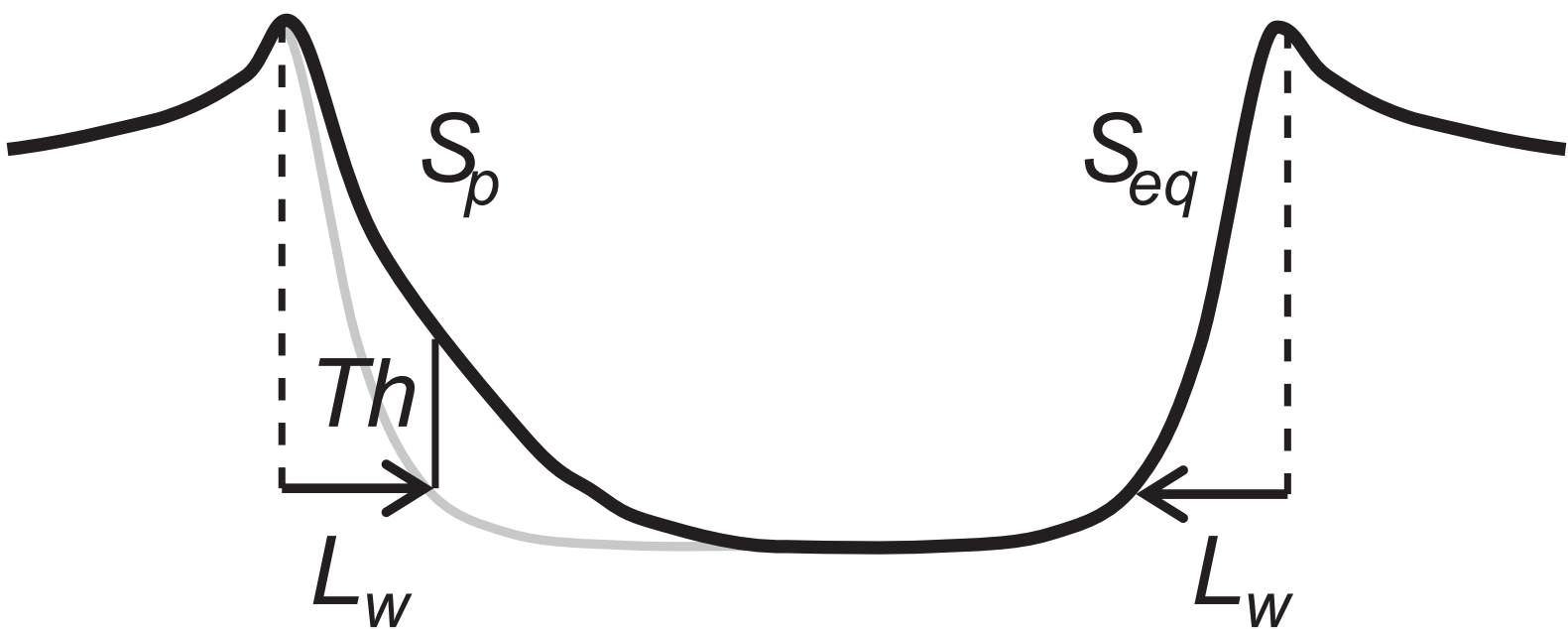


Figure 8 (colour)
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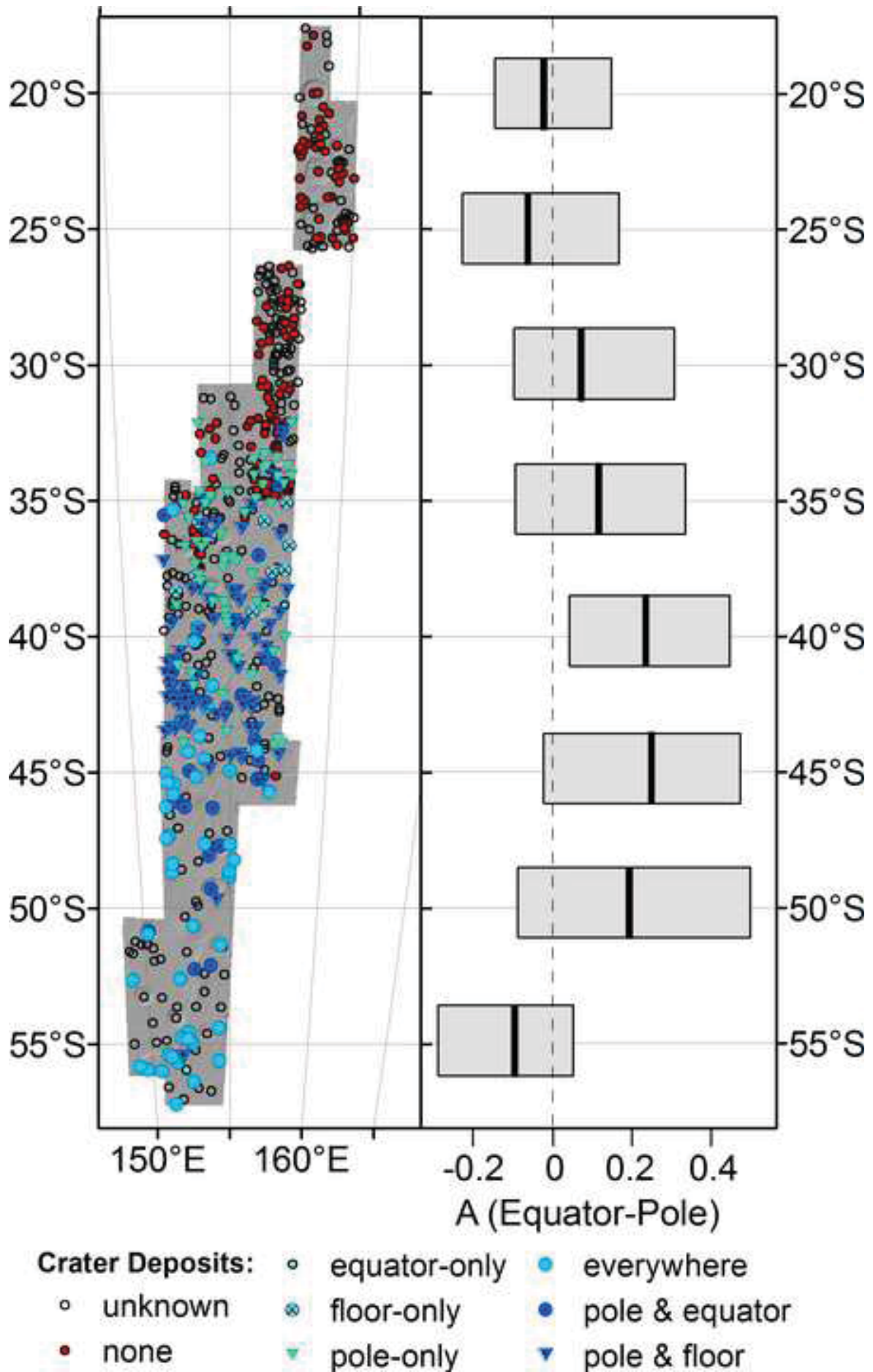
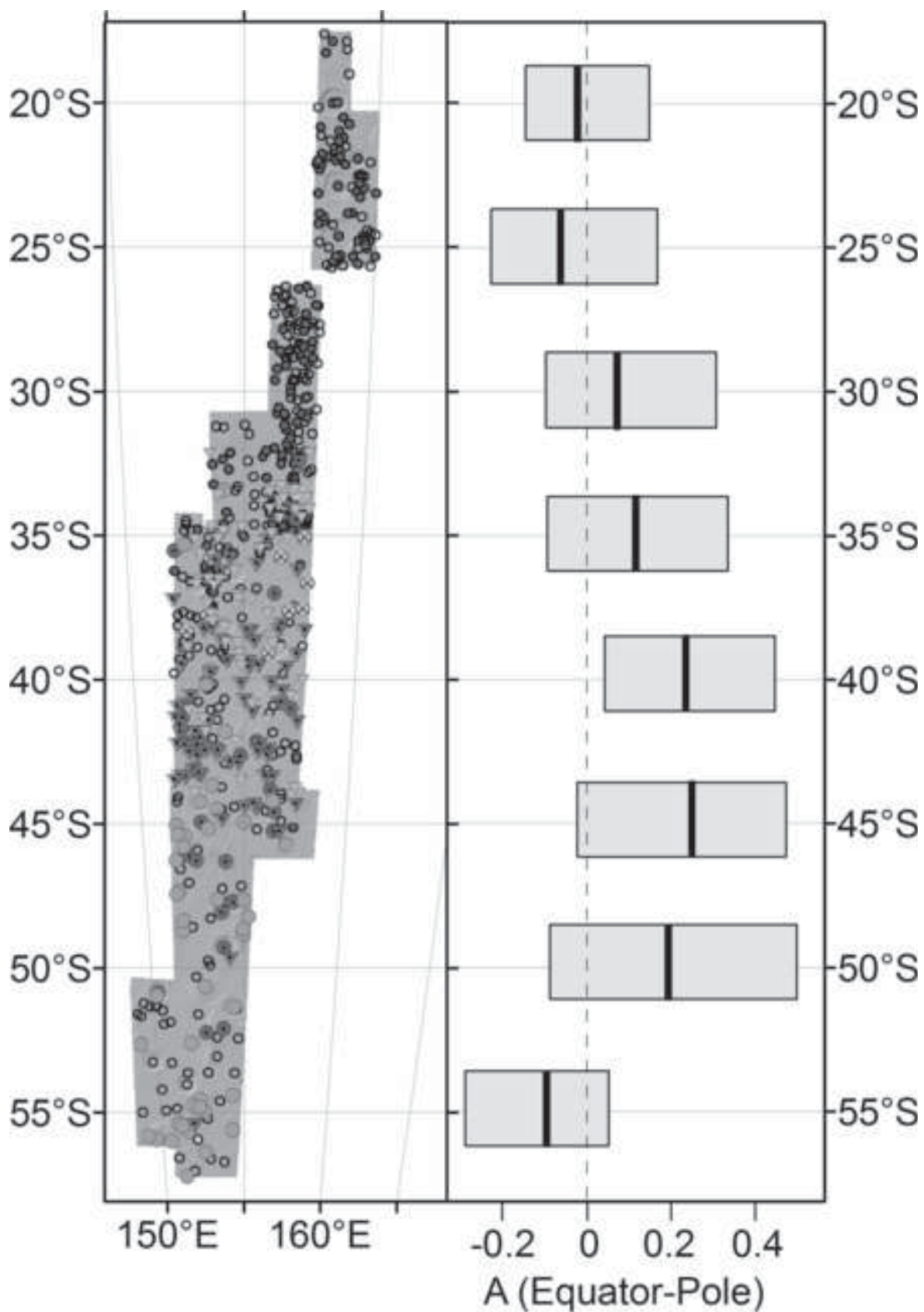


Figure 8
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Crater Deposits:

○ equator-only	● everywhere	
○ unknown	⊗ floor-only	● pole & equator
● none	▼ pole-only	▼ pole & floor