

Investigating the Linkage Between Spiral Trough Morphology and Cloud Coverage on the Martian North Polar Layered Deposits

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Abstract

The Martian North Polar Layered Deposits (NPLD) are composed of alternating water-ice and dust-rich layers resulting from atmospheric deposition and are key to understanding Mars' climate cycles. Within these deposits are spiral troughs, whose migration affects deposition signals. To understand the relationship between NPLD stratigraphy and Martian climate, we must identify modern-day drivers of NPLD ice migration. Prevailing theory posits migration driven by upstream-migrating bed undulations bounded by hydraulic jumps, caused by katabatic winds flowing over trough walls with asymmetric cross-sectional relief. This is supported by trough-parallel clouds, whose formation has been attributed to hydraulic jumps.

We present a cloud atlas across the Martian north pole using ~13,800 THEMIS images spanning ~18 Earth years. We find trough-parallel clouds in ~400 images, with regions nearer to the pole having higher cloud frequency. We compare spiral trough geometry to our cloud atlas and find regions with trough-parallel clouds often correlate with metrics associated with modern-day sublimation-deposition cycles (i.e., relief and asymmetry), but not always. In some regions, troughs with morphologies conducive to cloud formation have no clouds. Overall, trough geometry varies greatly across the deposits, both within and between troughs, suggesting localized differences in deposition relative to migration, varying katabatic wind intensities, differing past climatic states influencing the troughs, varying trough initiation properties, or the possibility of additional mechanisms for trough initiation and migration (e.g., in-situ trough erosion). Understanding what controls trough shape variability across the NPLD and how these controls change through time and space is key when interpreting Martian paleoclimate. Abstract content goes here

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2 **Investigating the Linkage Between Spiral Trough Morphology and Cloud Coverage**
3 **on the Martian North Polar Layered Deposits**

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7 **Key Points:**

8 • The spiral troughs on Mars' northern polar layered deposits (NPLD) have highly variable
9 geometry, both within a trough and between troughs.

10 • The presence of trough-parallel clouds, indicative of katabatic jumps and active trough
11 migration, are regionally variable across the NPLD.

12 • Trough shape most conducive to the formation of katabatic jumps and generating clouds
13 is not as widespread as previously suggested.

14

15 **Abstract**

16 The Martian North Polar Layered Deposits (NPLD) are composed of alternating water-ice
17 and dust-rich layers resulting from atmospheric deposition and are key to understanding Mars’
18 climate cycles. Within these deposits are spiral troughs, whose migration affects deposition sig-
19 nals. To understand the relationship between NPLD stratigraphy and Martian climate, we must
20 identify modern-day drivers of NPLD ice migration. Prevailing theory posits migration driven by
21 upstream-migrating bed undulations bounded by hydraulic jumps, caused by katabatic winds flow-
22 ing over trough walls with asymmetric cross-sectional relief. This is supported by trough-parallel
23 clouds, whose formation has been attributed to hydraulic jumps. We present a cloud atlas across
24 the Martian north pole using ~13,800 THEMIS images spanning ~18 Earth years. We find trough-
25 parallel clouds in ~400 images, with regions nearer to the pole having higher cloud frequency. We
26 compare spiral trough geometry to our cloud atlas and find regions with trough-parallel clouds
27 often correlate with metrics associated with modern-day sublimation-deposition cycles (i.e., relief
28 and asymmetry), but not always. In some regions, troughs with morphologies conducive to cloud
29 formation have no clouds. Overall, trough geometry varies greatly across the deposits, both within
30 and between troughs, suggesting localized differences in deposition relative to migration, varying
31 katabatic wind intensities, differing past climatic states influencing the troughs, varying trough
32 initiation properties, or the possibility of additional mechanisms for trough initiation and migration
33 (e.g., in-situ trough erosion). Understanding what controls trough shape variability across the
34 NPLD and how these controls change through time and space is key when interpreting Martian
35 paleoclimate.

36 **Plain Language Summary**

37 The Martian North polar ice cap is composed of layers of water-ice and dust deposited
38 from the atmosphere, and differences in their thicknesses are thought to be the result of climate
39 variations. Interpretations of the climate recorded in these layers can be affected by other processes
40 that can deposit or erode ice. One process we need to understand is the migration history for the
41 large spiraling troughs that occur across the ice cap, which tend to have asymmetric wall slopes
42 and reliefs. The leading theory suggests that their migration is driven by ice ablation from winds
43 that flow down the higher trough wall, and deposition (and cloud formation) when the wind hits
44 the trough floor and decelerates. We present an updated record of cloud coverage across the ice
45 cap using orbital images spanning ~18 Earth-years and analyze ~3000 trough cross-sections to
46 compare trough shape to cloud location. We find regions with clouds often correlate with trough
47 shapes associated with modern-day sublimation-deposition cycles (wall asymmetry), but often
48 asymmetric troughs have no clouds, or the troughs are symmetric. The fact that trough shape
49 changes across the ice cap suggests ice transport processes are variable and need to be considered
50 when interpreting paleoclimate.

51 **1 Introduction**

52 [1] The polar regions of Mars are composed of atmospherically deposited water ice and
53 dust layers (Cutts, 1973) that record Mars' climate and hydrosphere over the lifetime of the depos-
54 its. These deposits can be divided into the South Polar Layered Deposits (SPLD) and the North
55 Polar Layered Deposits (NPLD), of which the NPLD are younger and better characterized (Her-
56 kenhoff and Plaut, 2000; Laskar et al., 2002, 2004; Levrard et al., 2007). Like terrestrial polar ice
57 caps, the thickness and composition of individual layers potentially offer insight to insolation-
58 controlled climatic variations in the deposition of ice and dust on Mars (Smith et al., 2018). Un-
59 derstanding the stratigraphic record of these deposits is therefore important for understanding

60 modern Martian climate, the relationship between climate and surface processes, and volatile res-
61 ervoirs on Mars (e.g., Diniega and Smith, 2020; Smith et al., 2020).

62 [2] At the north pole, the NPLD is a part of Planum Boreum, the northern polar plain on
63 Mars consisting of a low-albedo sand and ice deposit (Malin & Edgett, 2002), and is a near-circular
64 structure stretching $\sim 1,000$ km across and ~ 3 km above the surrounding landscape (Tanaka et al.,
65 2008). The upper layers of the NPLD are exposed by spiral troughs, ~ 400 m to ~ 1000 m deep
66 depressions that spiral counterclockwise (Howard et al., 1982). In cross-section, these troughs have
67 been shown to have a high elevation and low elevation side, where the high-side is generally equa-
68 tor-facing, has a low albedo and is characterized by layered terrain, whereas the low-side is gen-
69 erally pole-facing, has an intermediate albedo (between that of the high-side and the inter-trough
70 regions) and has a mantling that is referred to as banded terrain (Howard et al., 1982). Early studies
71 of exposed layering in trough walls attempted to use ice layer thickness as a record of ice and dust
72 deposition rates driven solely by changes in Mars' orbit and axial tilt, not accounting for lateral
73 ice transfer (Cutts & Lewis, 1982; Fishbaugh et al., 2010; Howard et al., 1982; Hvidberg et al.,
74 2012; Laskar et al., 2002; Levrard et al., 2007). However, geomorphic and modeling studies of
75 individual troughs have shown that they migrate poleward through a combination of lateral ice
76 transport by wind and insolation-driven sublimation (i.e., Bramson et al., 2019; Howard et al.,
77 1982; Smith and Holt, 2010). Smith and Holt (2010) used radar data from the Shallow Radar
78 (SHARAD) instrument onboard the Mars Reconnaissance Orbiter (MRO) to show that subsurface
79 geometry and layering within the NPLD was also indicative of constructional trough migration,
80 likely due to wind transport and atmospheric deposition. As such, this large-scale lateral ice
81 transport on the NPLD will affect apparent deposition rates and layer thicknesses through time
82 (Howard et al., 1982; Howard, 2000).

83 [3] Based on observations as well as modeling studies, the general conceptual model for
84 trough migration is that ice is laterally transported through cyclic step migration driven by kata-
85 batic winds, which cause katabatic (or hydraulic) jumps in regions where wind rapidly decelerates
86 (Smith et al., 2013), combined with ice loss from sublimation (predominantly on the equator-fac-
87 ing trough slopes) (Bramson et al., 2019). Katabatic winds are some of the most common winds
88 on long, planetary slopes and are most often found on Earth near elevated ice sheets. Lied (1964)
89 and Pettré and André (1991) identified clouds associated with katabatic jumps in Antarctica, and
90 similar clouds were identified within the spiral troughs, leading to the hypothesis that clouds were
91 evidence of active sublimation and deposition (Smith et al., 2013). Smith et al. (2013) examined
92 over 10-years of Thermal Emission Imaging System (THEMIS) imagery to map near-surface
93 clouds across the NPLD to identify trends in their timing, location, and morphology. They showed
94 that clouds occurred between L_s 24 and L_s 102, with the highest frequency of coverage occurring
95 around the Martian summer solstice (L_s 80-90) (Smith et al., 2013). Near-surface clouds were also
96 found to form predominantly near the spiral troughs and were either transverse or parallel to the
97 trough, indicating cloud formation was strongly influenced by topography (Smith et al., 2013).
98 Their estimates of Froude numbers, wind velocity, and wind depths based on locations with cloud
99 presence were found to be consistent with conditions associated with katabatic wind on Earth
100 (Smith et al., 2013).

101 [4] Taken together prior work suggests that clouds serve as a proxy for modern-day lateral
102 ice transport and spiral trough migration due to katabatic winds (Smith et al., 2013). However, the
103 conclusions made by Smith et al. (2013) were based on data taken over ~10 years of the Martian
104 cloud record, whereas there are now 18 years of data. Also, the katabatic wind-driven sublimation
105 and deposition model assumes troughs have asymmetric wall reliefs, with a high-side

106 (sublimation) and a low-side (deposition), but the variability in trough morphology across the en-
107 tire NPLD is unknown. Here, we expand on the work of Smith et al. (2013) by building an updated
108 cloud atlas to understand where and how frequently clouds occur on the NPLD. We then test
109 whether there are regional patterns in surface trough morphology, as regions have previously been
110 distinguished across the NPLD based on their surface characteristics and subsurface layering
111 (Smith & Holt, 2015). Lastly, we investigate if troughs with persistent cloud coverage over the last
112 ~20 years are morphologically different (i.e., comparing cross-section shape, wall slopes, relief)
113 than troughs in regions of inactive or no clouds.

114 **2 Methods**

115 2.1 Trough Cloud Imagery

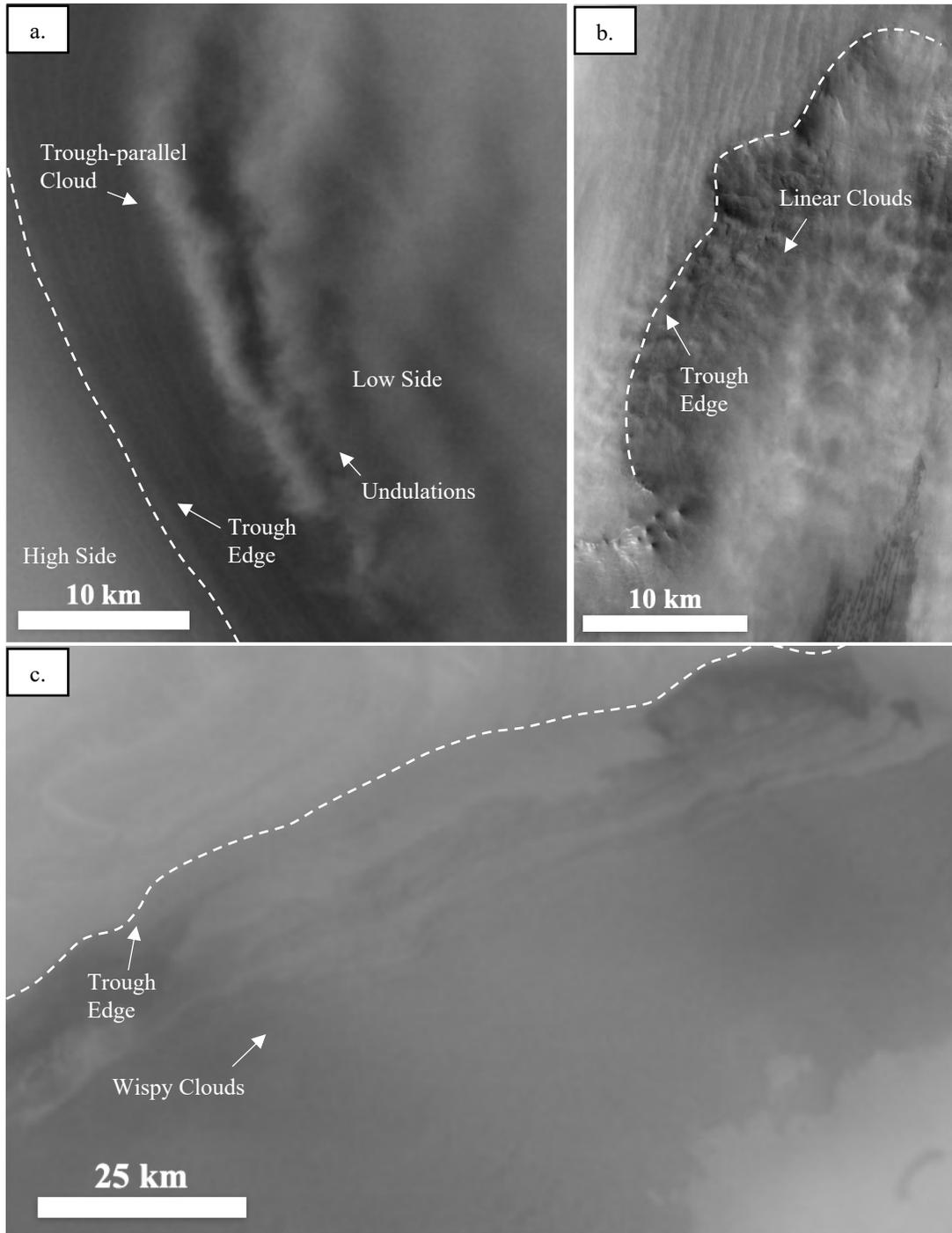
116 [5] As of June 2022, there were 13,857 Thermal Emission Imaging System (THEMIS)
117 visible light spectrometer (VIS) images of the Martian north polar region (northward of 82°) avail-
118 able on Arizona State University’s Mars Image Explorer for Mars years 26–35 (Christensen et al.,
119 2004). We examined each of these THEMIS VIS images for quality, the presence or absence of
120 clouds, and cloud type (when present).

121 [6] To quantify image quality, we assigned a metric gauging whether the image was visu-
122 ally clear enough to distinguish clouds. This metric was based primarily on if surface features
123 could be visibly distinguished in the image (e.g., pitting, craters, trough wall layers, trough edges,
124 striations, etc.). A ranking of 0 means the surface features are clear and high-resolution; 1 means
125 surface features are visible but less resolved in some way (e.g., slightly blurred, washed out,
126 blocked by some visual artifacts, etc.); 2 means the surface features are not at all distinct or blocked
127 out by large visual artifacts, and the image is classified as too noisy to credibly decide if clouds

128 are or are not present. We only used images with a rank of 0 and 1 for subsequent analyses, though
129 all images and their assigned rankings can be found in the associated data repository.

130 [7] Images were then classified as either having cloud presence or absence, on a yes/no
131 scale. To state “yes”, the cloud’s edge must be distinct from the NPLD surface, so as not to confuse
132 the cloud with other surface features. This was particularly important for images with a noise rank
133 of 1. If there was doubt if the feature is a cloud (e.g., due to a soft or no cloud boundary with the
134 surface and/or image defects on top of the potential cloud), that image is classified as “no” in this
135 analysis. If clouds were identified they were classified into three broad categories: trough-parallel
136 clouds (similar to the low-altitude clouds with an elongated structure located parallel to the NPLD
137 troughs identified in Smith et al. (2013)), wispy clouds, and general cloudiness. When visible,

138 other related cloud features were noted, such as the presence of undulations, or linear cloud struc-
139 tures. Examples of some of these cloud types and features can be seen in Figure 1.



140

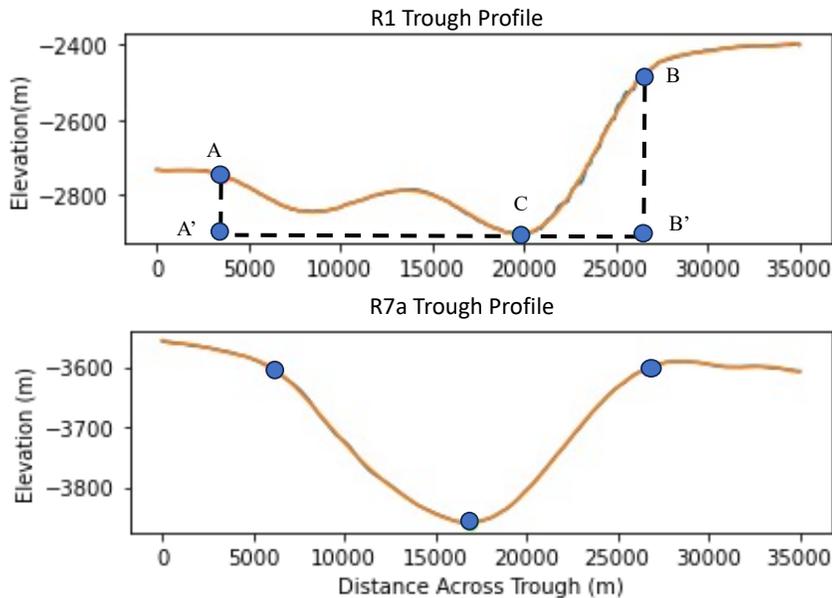
141 **Figure 1.** a.) THEMIS image V12325004 with trough-parallel, undular trough clouds, located in
142 R3. Note the trough-parallel cloud is located on the low side of the trough. b.) THEMIS image
143 V37081012 with linear trough clouds, located in R2, categorized as general cloudiness for this
144 study. c.) THEMIS image V64157020 with wispy trough clouds in R2, categorized as general
145 cloudiness for this study.

146 2.2 NPLD Trough Geometry

147 [8] We identified differences between trough morphology across the NPLD using cross-
148 sectional analysis. We extracted 3,192, 35 km long cross-sectional trough profiles, with profiles
149 taken every 5 km down-trough perpendicular to the trough thalweg. We used a HRSC and MOLA
150 Blended 200m DEM (v2) (Ferguson et al., 2018) resampled to 1000m/pixel, to reduce noise but
151 retain trough shape information. Our specific resampling ratio was chosen by comparing unsam-
152 pled (200m/pixel) trough metrics to resampled profiles at 500m/pixel, 1000m/pixel, 2000m/pixel,
153 and 3000m/pixel (larger resampling sizes would compromise our 5 km profile spacing). The metric
154 values for each resampling ratio were compared to the original unsampled ratio (200m/pixel) met-
155 ric values, selecting for the largest resampling ratio that did not have statistically different results
156 from the unsampled ratio, using a Mann-Whitney U Test (Mann & Whitney, 1947). This unsam-
157 pled and resampled comparison was done for two different troughs (~50 different profiles) on the
158 NPLD in region 1, a simple trough that had roughly the same cross-sectional shape for 115 km and
159 a complex trough that changed shape frequently, in order to select a ratio that would properly
160 capture both simple and complex trough metrics.

161 [9] We then calculated various trough metrics for every trough profile. To do this, all ex-
162 tracted trough profiles were mapped with a polynomial fit to smooth the trough profile. This

163 allowed us to automatically identify the trough shoulder points (A and B in Figure 2) by calculating
 164 the second derivative of the polynomial, and the trough minimum point (C in Figure 2) by calcu-
 165 lating the first derivative of the polynomial. Our trough metrics, illustrated in Figure 2, were pole-
 166 facing relief (A minus A'), equator-facing relief (B minus B'), relief difference (the difference
 167 between A minus A' and B minus B'), pole-facing slope (average slope between A and C), equator-
 168 facing slope (average slope between B and C), width (B' minus A'), and depth (the average of A
 169 minus A' and B minus B').



170

171 **Figure 2.** Examples of trough profiles (location of profiles shown in Figure 3) with key trough
 172 locations marked (blue circles) that were used to calculate the Pole/Equator relief, relief differ-
 173 ence, Pole/Equator slope, width, and depth. Pole-facing slope is calculated from point A to C;
 174 equator-facing slope from point B to C; pole-facing relief is calculated as the distance from point
 175 A to A'; equator-facing relief is the distance from B to B'; relief difference is the difference be-
 176 tween pole-facing and equator-facing relief; depth is the averaged relief value; width is the dis-
 177 tance from A' to B'. Note the distinct shape differences between the two troughs, specifically that

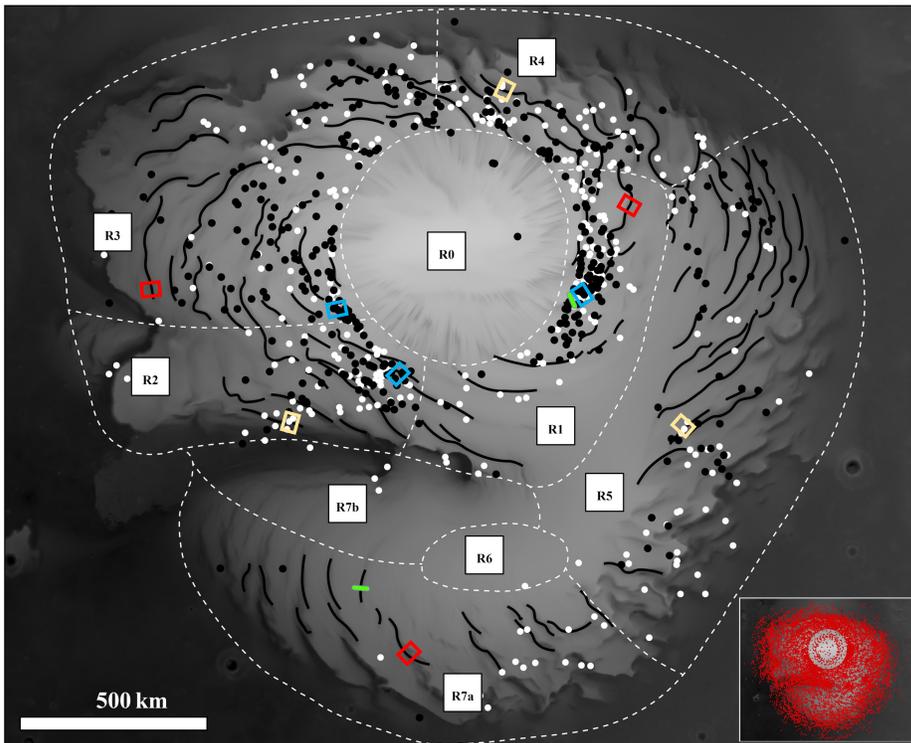
178 the R1 trough has notably asymmetric relief height while the R7a trough has symmetric relief
179 height. The R1 trough also has a central peak (often referred to as a central promontory, (Smith
180 & Holt, 2015)) between points A and C. Vertical exaggeration $\sim 1/20$ for the R1 trough profile
181 and $\sim 1/30$ for the R7a profile.

182 **3 Results**

183 3.1 Updated NPLD Cloud Atlas

184 [10] Our study identified ~ 800 THEMIS images out of the total $\sim 13,800$ that had clouds
185 (Figure 3, inset), and of those, ~ 400 were identified as near-surface trough-parallel clouds (black
186 circle, Figure 3), with $\sim 33\%$ of those being undular trough-parallel clouds (Figure 1a). Of the
187 remaining images, $\sim 5\%$ contained linear cloud features (Figure 1b), $\sim 16\%$ contained wispy cloud
188 features (Figure 1c), and the remainder showed general cloudiness. As seen in Figure 3, cloud
189 coverage across the NPLD is not uniform, both for clouds in general (white points) and for trough-
190 parallel clouds (black points). Most clouds were observed to be associated with troughs and either
191 centered around the pole or seen on the outer margins of the deposit. In terms of total cloud obser-
192 vations from all THEMIS imagery (Table 1), region 1 has the highest percentage, with $\sim 9\%$, fol-
193 lowed by regions 2, 3 and 4 ($\sim 6-7\%$), and then region 5 ($\sim 4\%$). Region 7a and 7b only had $\sim 1\%$
194 and there were no clouds observed in region 6. When normalized by the total number of images
195 with clouds (726 images), almost 30% were in region 3, 23% were in region 1, and regions 2, 4,
196 and 5 had 12 to 17%. The remaining regions had less than 5% (Table 1). When considering trough-
197 parallel clouds only, regions 1 and 3 had the highest percentage when normalized by all THEMIS
198 images ($\sim 4.5\%$), which includes $\sim 60\%$ of all identified trough-parallel clouds (Table 1). Regions
199 2 and 4 had $\sim 3\%$, followed by region 5 (2%). Regions 6 and 7a and 7b, all broadly within the

200 Gemina Lingula region of the NPLD, had very few to no trough parallel cloud observations (0%,
 201 0.2%, and 0% respectively). Taken together, regions 1 and 3 tend to have the highest number of
 202 clouds, including trough-parallel clouds, followed by regions 2, 4 and 5. Regions 6 and 7 (a and
 203 b) have few to no clouds. This low frequency of clouds is important to note as region 7a does have
 204 a significant number of troughs per area.



205

206 **Figure 3.** A map of the NPLD where THEMIS images with trough-parallel clouds (black circles)
 207 and general cloudiness (white circles) were identified in this study. The green lines indicate the
 208 location of the R1 and R7a trough profiles displayed in Figure 2. The red outlines correspond to
 209 the profile metric data classified as “No Clouds” for our statistical testing shown in Table 3. The
 210 yellow outlines correspond to the profile metric data classified as “General Cloudiness” for our
 211 statistical testing shown in Table 3. The blue outlines correspond to the profile metric data

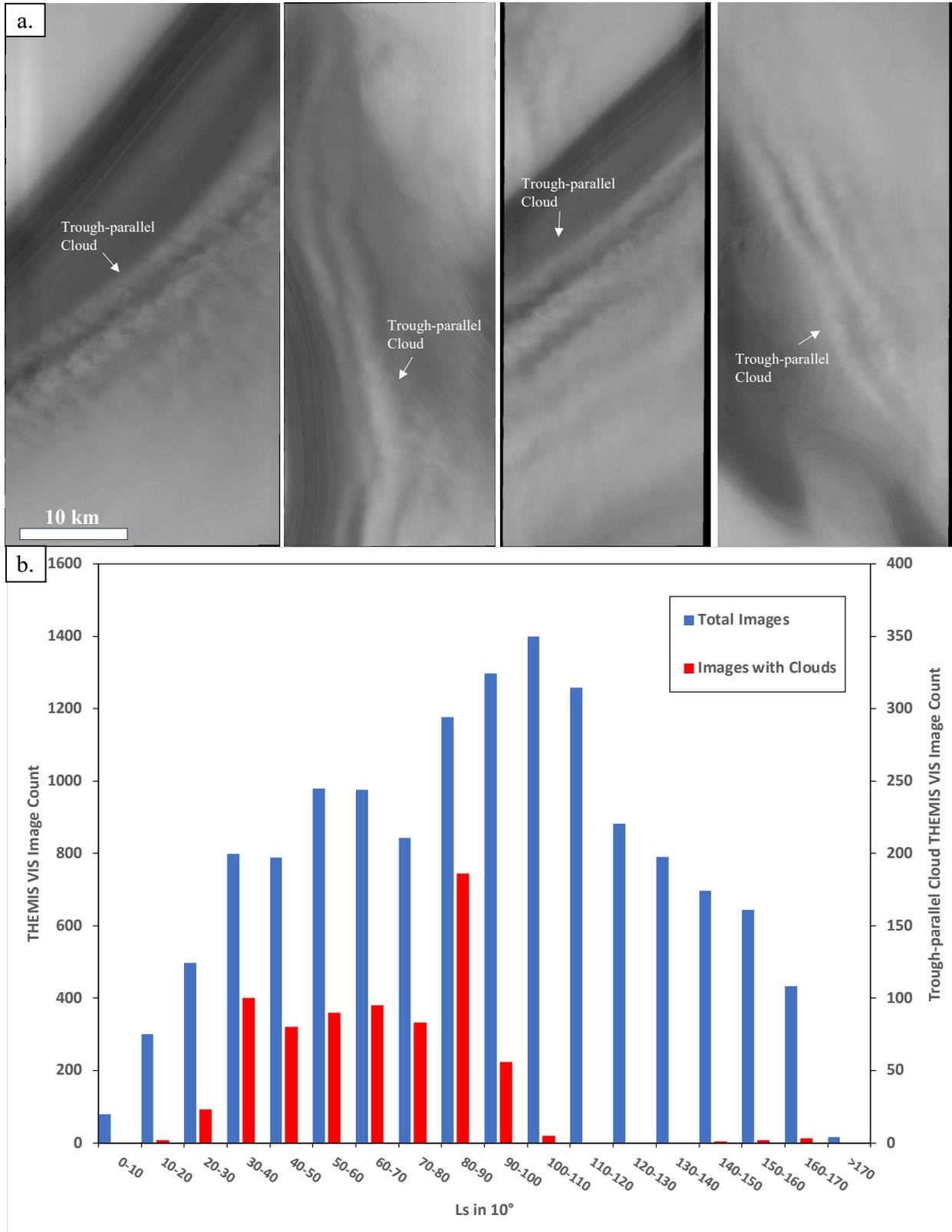
212 classified as “High Frequency of Trough-Parallel Clouds” for our statistical testing shown in Ta-
213 ble 3. The sub-figure displays the locations of all THEMIS imagery investigated in this study,
214 marked by red circles.

Regions	Number of Images	Number of Images w/ TP Clouds	Ratio TP Clouds/Total Images in Region	Number of Images w/ Clouds	Ratio Clouds/Total Images in Region	Trough Cloud Types Identified in Region
Region 1	1,874	84 (22%)	0.045	164 (23%)	0.088	General, wispy, linear, TP (high presence), undular TP
Region 2	1,994	55 (14%)	0.028	126 (17%)	0.063	General, wispy, linear, TP, undular TP
Region 3	3,021	141 (37%)	0.047	206 (28%)	0.068	General, wispy, linear, TP (highest presence), undular TP
Region 4	1,648	49 (13%)	0.03	113 (16%)	0.069	General, wispy, TP, undular TP
Region 5	2,499	47 (12%)	0.019	88 (12%)	0.035	General, wispy, linear, TP, undular TP
Region 6	120	0 (0%)	0	0 (0%)	0	No clouds seen
Region 7a	1,605	4 (1%)	0.002	23 (3.1%)	0.014	General, wispy, TP (lowest presence)
Region 7b	890	0 (0%)	0	6 (0.8%)	0.007	General, wispy
TOTAL	13,857	380	0.027 (2.7%)	726	0.052 (5.2%)	

215 **Table 1.** Number of THEMIS images investigated in this study broken down by region (based on
216 regions delineated in Smith and Holt, 2015) as well as the number and percentage of those images
217 where any clouds, and specifically trough-parallel clouds, were observed. Trough-parallel is short-
218 ened to TP in this table.

219 [11] Cloud coverage has seasonal variations and trends over time (Figure 4b). Similar to
220 seasonal patterns identified by Smith et al. (2013) for Mars years 26 – 31, the earliest clouds each
221 year were observed during Mars’ north polar spring, with the highest frequency of clouds occurring
222 slightly later in the spring. No clouds are identified during Mars’ north polar winter, or dust storm
223 season. It is important to note that almost no images are taken during Mars’ north polar fall or
224 winter, including during dust storm season, and the few that exist are entirely dust covered, so
225 there is no way visually to note whether trough clouds are in fact present during this time. Addi-
226 tionally, there are fewer THEMIS images earlier in the Mars year as compared to the high fre-
227 quency of imaging in late spring to early summer (Figure 4b). This means that locations on the
228 NPLD that could be more prone to cloud coverage earlier in the Mars year are being imaged less
229 frequently compared to those prone to cloud overage later in the season. Both factors limiting
230 imaging in specific Mars seasons should be noted as potential causes of sampling bias in our

231 results, where we are potentially missing clouds present early or later in the Mars year due to a
232 lack of THEMIS imaging coverage.



234 **Figure 4.** a.) Additional examples of THEMIS images with trough-parallel clouds; from left to
235 right V29043038, V45756001, V62430037, V78928031. b.) Temporal histogram of clouds. The
236 ~13,500 THEMIS VIS images were examined for clouds over Mars years 26–35 (blue bars).
237 ~400 images capture clouds like those depicted in a) and in Figure 1a (red bars). Clouds imaged
238 by THEMIS begin after Ls 14, spike between Ls 30 and 40, peak between Ls 80 and 90, then ta-
239 per off sharply near Ls 100. The last trough-parallel cloud is observed at Ls 168.

240 3.2. Regional Trough Profile Morphology

241 [12] We compared our trough profile metrics, as defined in Section 2.2, across the NPLD
242 to identify any regional trends (Figures 5-8; S1). We found that trough profile depths (Figure 5a)
243 varied between ~30 m and ~980 m across the entirety of the deposit. This is similar to depths noted
244 by Pathare and Page (2005), who report depths of 200-900 m for the select troughs they investi-
245 gated. Regions 1 and 5 had similar depth distributions with most troughs being between 100 m and
246 300 m deep, with a mean of ~210 m (median ~208 m). Regions 3 and 7a had a larger range of
247 depths, ~100 m to 500 m, with a mean depth of ~260 m for region 3 (median ~250 m) and ~308
248 m for region 7a (median ~282 m). Region 4 had generally deeper troughs, ranging between ~200
249 m and ~600 m, with a mean of ~365 m (median ~354 m). Region 2 had the most uniform distri-
250 bution of trough depths, ranging between ~100 m and ~600 m (mean ~326 m and median ~ 313
251 m).

252 [13] Trough profile widths (Figure 5b) ranged from ~7 km to ~34 km across the deposit.
253 Most of the troughs in regions 2 and 5 were between ~10 km and ~27 km, with a mean width of
254 ~18 km (median ~17 km). Regions 3 and 4 had generally larger trough widths than the troughs in
255 region 2 and 5, with values between ~13 km and ~30 km (mean of ~20 km and median of ~21 km

256 for both regions). Region 1 had the narrowest troughs on average, with most between ~5 and ~25
257 km (mean and median ~15 km), and the narrowest troughs observed across the NPLD were those
258 in Region 1. Region 7a was the most uniformly distributed, with widths between ~10 km and ~33
259 km (mean ~19 km, median ~18 km).

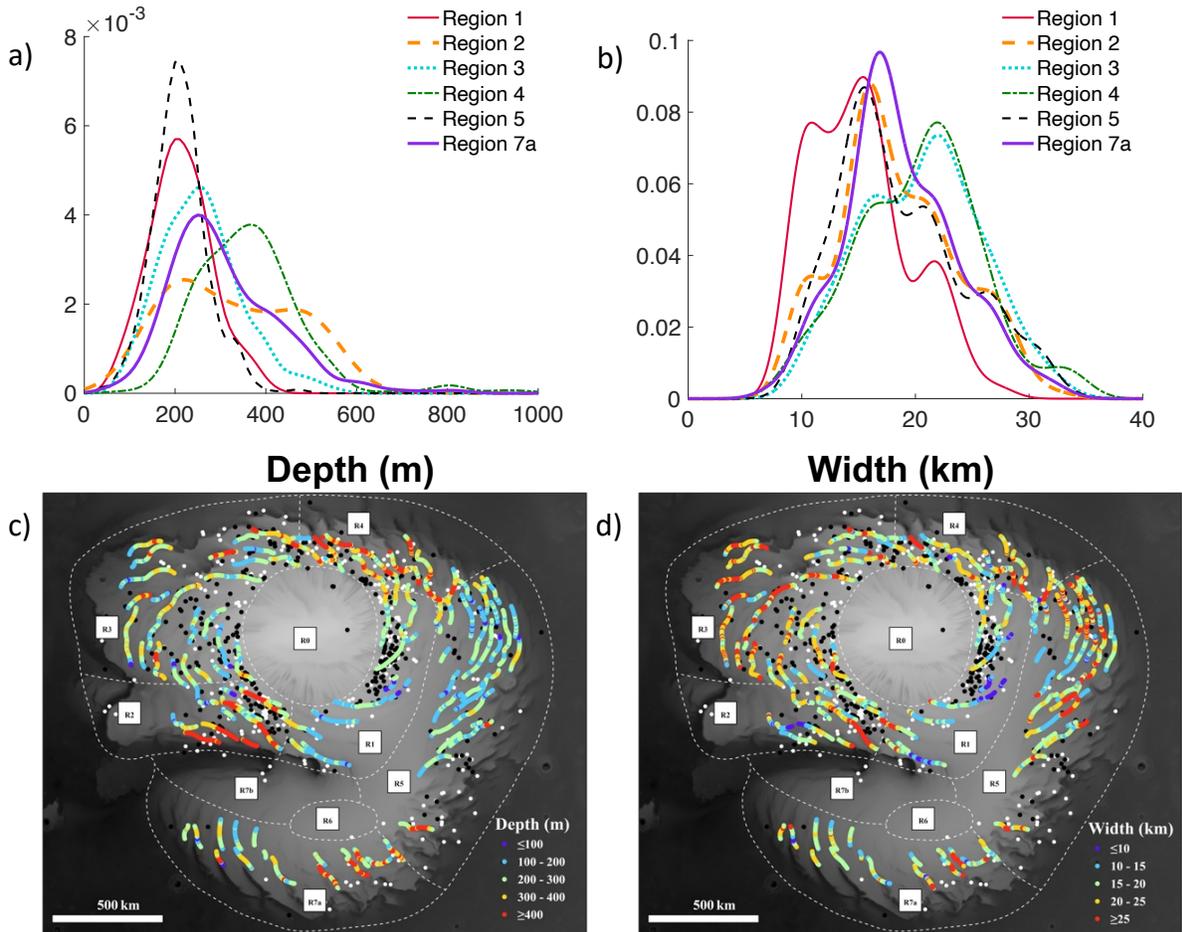
260 [14] Pole-facing wall slopes (Figure 6a) ranged from ~0.006 to ~5 degrees across the
261 NPLD, but in all regions most of the walls were between 0.25 and 3.5 degrees with a mean (and
262 median) of ~1-1.7. Equator-facing wall slopes (Figure 6b) had a similar range of values as com-
263 pared to pole-facing wall slopes (~0.006 to ~7 degrees), though there was more variability by
264 region. Regions 3 and 5 had shallower equator-facing wall slopes on average (mean ~1.6 to 1.8
265 degrees and median ~1.6 to 1.7 degrees), while region 1, 4, and 7a tended to be slightly steeper,
266 with means of ~2, ~2.6, and ~2.1 degrees, respectively. Region 2 was more broadly distributed,
267 with wall slopes falling between ~0.4 and ~6 degrees and had a mean of ~2.6.

268 [15] Pole-facing relief (Figure 7a) ranged from ~0.5 m to ~744 m across the NPLD, with
269 regions 1, 3, and 5 having reliefs between ~0 m and ~350 m, though regions 3 and 5 have means
270 of ~150 m while region 1 has a mean ~126 m. Regions 2, 4, and 7a had a broader distribution of
271 reliefs (between ~0 m and ~500 m) and were steeper and their average reliefs ranged from ~215-
272 240 m (Figure 7a). Equator-facing wall relief (Figure 7b) ranged from ~0.4 m to ~1280 m across
273 the deposit, but the distributions in relief varied more by region than those for pole-facing relief.
274 Equator-facing reliefs in region 1 fell between ~50 and ~600 m (with a mean of ~300 m), but had
275 a bimodal distribution with a larger peak at ~200 m and a second smaller peak at ~400 m. Equator-
276 facing reliefs for regions 3 and 7a ranged between ~50 m and ~750 m, with a mean of ~361 m and
277 ~374 m respectively (median ~345 m and ~352 m). Region 5 had a slightly narrower distribution
278 of equator-facing reliefs as compared to other regions, ranging from ~50 m to ~450 m, though the

279 mean and median (~274 m and ~270 m) were close in value to those of region 1. Regions 2 and 4
280 tended to have higher equator-facing reliefs (means of ~436 m and ~505 m respectively), though
281 Region 2 was slightly bimodal with a main peak at ~400 m and a smaller peak at ~700 m.

282 [16] When investigating wall asymmetry (i.e., differences in wall relief across a trough
283 profile) (Figure 8a), we found that asymmetry ranged from ~0 m to ~800 m across the NPLD. As
284 expected from its distributions in pole- and equator-facing relief, relief differences in region 1 were
285 bimodally distributed, with peaks at ~100 m and ~300 m. The different peaks appear spatially
286 distributed, with troughs in R1 located closer to R4 all having larger relief differences and those
287 closer to R2 having smaller relief difference. The values of those troughs located near R4 also
288 matches R4 relief difference values closely. Regions 2 and 3 were more widely and uniformly
289 distributed, with relief differences varying between ~100 m and ~800 m. Region 4 had the largest
290 relief differences, averaging ~300 m, while region 5 had the smallest (~130 m). Region 7a was the
291 most right-skewed, having the highest density of trough profiles with negligible asymmetry. Based
292 on the distribution of trough metrics investigated herein, there is not a clear pattern that emerges
293 regarding regional distinctions in trough morphology. For example, the scale of troughs in regions
294 1 and 5 based on their width and depth are quite similar, but most troughs in region 5 have relief
295 differences of ~100 m whereas region 1 is more bimodal, with trough differences of ~100 m or
296 ~300 m. Similarly, troughs in regions 2 and 7a are also comparable in size regarding their width
297 and depth, but region 2 has generally greater relief differences and a greater distribution of wall

298 slopes.



299

300 **Figure 5.** a) Probability distribution function (PDF) curves of the depth data, plotted by region.

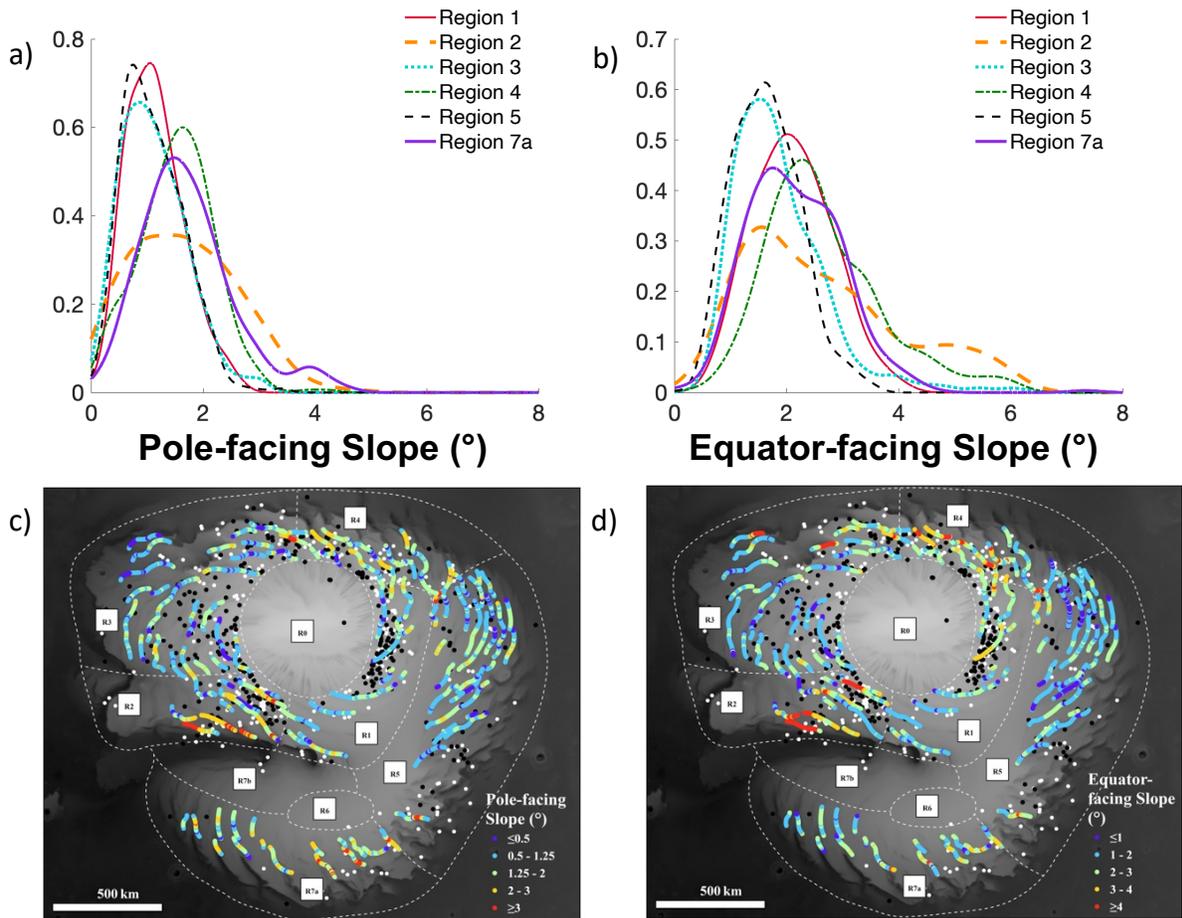
301 R0, R6, and R7b are not included as they have no troughs. b) Same as (a) but for trough width. c)

302 A map of the NPLD with trough depth data plotted as compared to THEMIS images with trough-

303 parallel clouds (black circles) and general cloudiness (white circles) that were identified in this

304 study. d) same as (c) but for width.

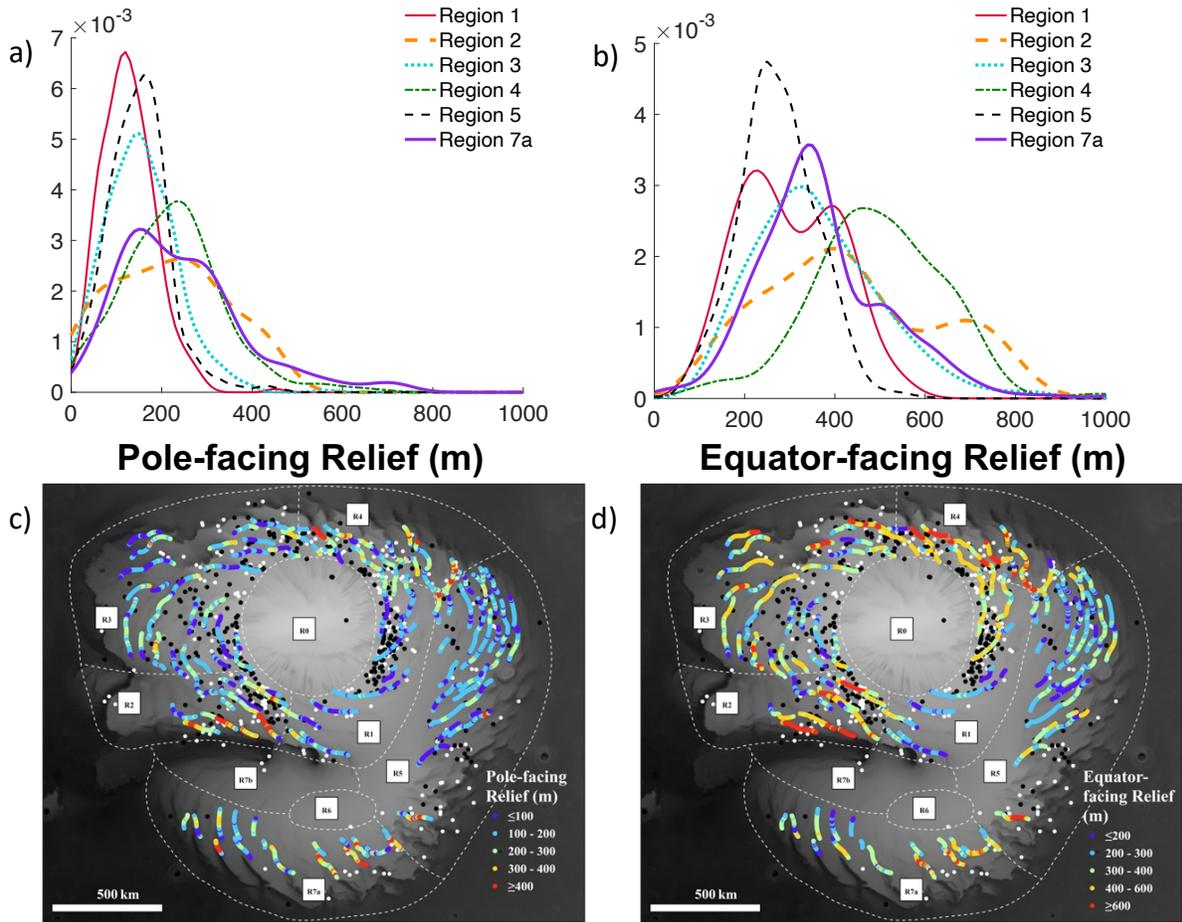
305



306

307 **Figure 6.** a) Probability distribution function (PDF) of the pole-facing slope data, plotted by re-
 308 gion. b) same as (a) but for equator-facing slope. c) A map of the NPLD with trough pole-facing
 309 slope data plotted as compared to THEMIS images with trough-parallel clouds (black circles)
 310 and general cloudiness (white circles) that were identified in this study. d) same as (c) but for
 311 equator-facing slope.

312

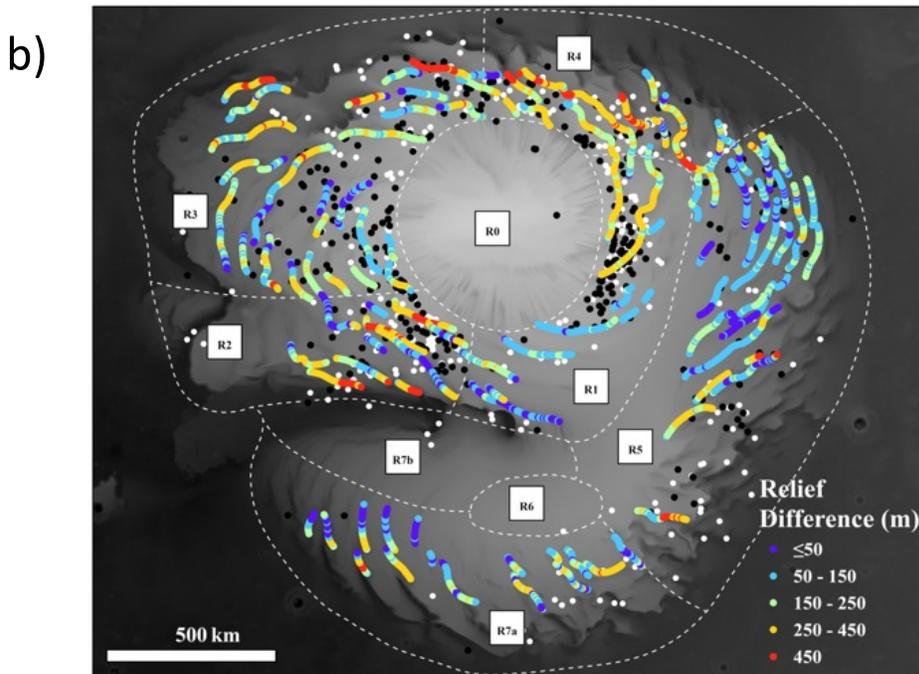
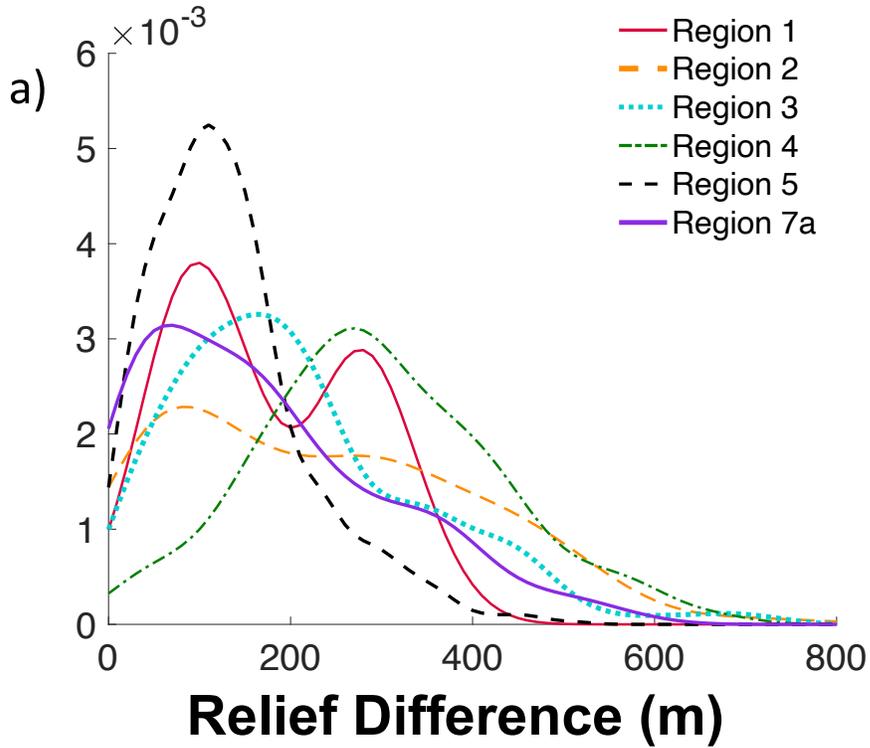


313

314 **Figure 7.** a) Probability distribution function (PDF) curves of the pole-facing wall relief data,
 315 plotted by region. b) same as (a) but for equator-facing wall relief. c) A map of the NPLD with
 316 trough pole-facing wall relief data plotted as compared to THEMIS images with trough-parallel

317 clouds (black circles) and general cloudiness (white circles) that were identified in this study. d)

318 same as (c) but for equator-facing wall relief.



319

320 **Figure 8.** a) Probability distribution function (PDF) curves of the pole-facing relief data, plotted
 321 by region. b) A map of the NPLD with trough wall relief difference data plotted as compared to
 322 THEMIS images with trough-parallel clouds (black circles) and general cloudiness (white cir-
 323 cles) that were identified in this study.

324 [17] We also conducted statistical testing to identify if our trough metrics were significantly
 325 different from each other when grouped by region. First, we used a Kruskal-Wallis Test (Kruskal
 326 & Wallis, 1952), a non-parametric test to identify if two or more datasets originate from the same
 327 distribution, to identify if, for example, trough profile widths from one region were significantly
 328 different from another region. If the p-value calculated from this test was below 0.05 for 95%
 329 confidence, we could reject the null hypothesis that the distribution of a given metric was not
 330 significantly different between regions. As this test only identified if *any* of the regions had signif-
 331 icantly different distributions and did not identify which regions were significantly different from
 332 one another, a post-hoc Dunn's test was conducted to identify which specific regions were signif-
 333 icantly different (Table 2). We confirmed that while some regions are statistically different from
 334 one another (e.g., regions 1 and 2 are significantly different across all but one metric), those same
 335 regions are similar to other regions based on individual metrics (e.g., region 2 can't be distin-
 336 guished from region 5 by width or regions 3 for relief difference). As such, we find that the regions
 337 delineated by Smith and Holt (2015), which were based on a combination of surficial characteris-
 338 tics (i.e., regional topographic slope, trough wavelength, terrain type) and subsurface (i.e., reflector
 339 morphology) characteristics, were not readily distinguishable by the metrics investigated here.

Width	R1	R2	R3	R4	R5	R7a		Depth	R1	R2	R3	R4	R5	R7a
R1		S	S	S	S	S		R1		S	S	S	NS	S
R2			S	S	NS	NS		R2			S	S	S	NS

R3				NS	S	S		R3				S	S	S
R4					S	S		R4					S	S
R5						NS		R5						S
Pole	R1	R2	R3	R4	R5	R7a		EQ	R1	R2	R3	R4	R5	R7a
Slope								Slope						
R1		S	NS	S	NS	S		R1		NS	S	S	S	NS
R2			S	NS	S	NS		R2			S	S	S	NS
R3				S	NS	S		R3				S	S	S
R4					S	NS		R4					S	S
R5						S		R5						S
Pole	R1	R2	R3	R4	R5	R7a		EQ	R1	R2	R3	R4	R5	R7a
Relief								Relief						
R1		S	S	S	S	S		R1		S	S	S	S	S
R2			S	NS	S	NS		R2			S	S	S	S
R3				S	NS	S		R3				S	S	NS
R4					S	NS		R4					S	S
R5						S		R5						S
Relief	R1	R2	R3	R4	R5	R7a								
Diff														
R1		S	NS	S	S	NS								
R2			NS	S	S	S								
R3				S	S	S								
R4					S	S								
R5						S								

340 **Table 2.** Results of statistical testing of trough metrics as compared between regions. If the distri-
 341 butions of the datasets are significantly different from one another the value S, short for *Significant*,

342 is recorded; if the distributions of the datasets are not significantly different from one another the
343 value NS, short for *Not Significant*, is recorded.

344 3.3. Linking Cloud Presence with Trough Morphology Metrics

345 [18] To understand how trough-parallel cloud presence or absence linked to our trough
346 morphology metrics, sections of the NPLD were visually identified that had high trough-parallel
347 cloud presence (blue boxes, Figure 3), low trough-parallel cloud presence but high presence of
348 other cloud types (yellow boxes, Figure 3), and both low trough-parallel cloud and other cloud
349 type presence (red boxes, Figure 3). Three 25 km long sections of these three subtypes, consisting
350 of 5 trough profiles each, were selected to compare metrics in these regions and note if they were
351 statistically significantly different from one another. We followed the same statistical procedure as
352 outlined in section 3.2 (i.e., a Kruskal-Wallis Test followed by a post-hoc Dunn's Test if the null
353 hypothesis could be rejected). We found statistically significant links (i.e., p-values < 0.05 with
354 95% confidence) between cloud presence and trough wall relief difference (Table 3), as there was
355 a significant difference between all three subtypes, but in general, cloud subtype did not have
356 statistically significant trends with trough profile morphology (Table 3). For example, for relief
357 difference in Figure 8b, we see that when trough-parallel clouds are present (black dots), wall
358 asymmetry is typically >50m. This is especially true in region 1, where trough-parallel clouds are
359 associated with wall relief differences between ~250 and ~450 m, such that wall morphology ap-
360 pears like that in Figure 2a. However, in many troughs across the NPLD, there are similarly asym-
361 metric walls (e.g., region 7a) and no trough-parallel clouds were observed. There is also a region
362 in region 2 (85.8 N, 330 E), where wall asymmetry is negligible (< 50 m and with cross-sectional

363 profiles like that in 3b), but a cluster of trough-parallel clouds were co-located. This region did
 364 however have a notably deep (>400 m, Figure 5c) and wide (>25 km, Figure 5d) section of trough.

Trough Metric	No Clouds vs General Cloudiness	No Clouds vs Trough-parallel Clouds	General Cloudiness vs Trough-parallel Clouds
Depth	Significant	Significant	Not Significant
Width	Significant	Significant	Not Significant
Pole-Facing Slope	Not Significant	Not Significant	Not Significant
EQ-Facing Slope	Significant	Not Significant	Not Significant
Pole-Facing Relief	Not Significant	Not Significant	Not Significant
EQ-Facing Relief	Significant	Significant	Not Significant
Relief Difference	Significant	Significant	Significant

365 **Table 3.** Table of the results of our statistical testing between the three subsections identified
 366 with different cloud presence/absence, outlined in Figure 3. If the distributions of the datasets are
 367 significantly different from one another the value *Significant* is recorded; if the distributions of
 368 the datasets are not significantly different from one another the value *Not Significant* is recorded.

369 4 Discussion

370 4.1 Cloud Distribution Across the NPLD

371 [19] Smith et al. (2013) looked at ~8,500 optical images from Mars years 26-31 (mostly
 372 from THEMIS but also from the High Resolution Stereo Camera (HRSC), Mars Orbiter Camera
 373 (MOC), Context Imager (CTX) and the High Resolution Imaging Science Experiment (HiRISE))
 374 and identified ~370 cloud images with elongated structures and of those ~350 were classified as
 375 having trough-parallel clouds in THEMIS images and another 6 were identified in other imagery
 376 (~4%). Our study looked at 13,857 THEMIS images, which extended the cloud survey of Smith
 377 et al. (2013) by eight more Earth years (Mars years 26 – 35), and we found ~400 images with
 378 definitive trough-parallel clouds (~2.7%). The fact we find ~25% less images with trough-parallel
 379 cloud occurrence than previously is likely due to our image quality assessment, such that any

380 images where clouds might have been present, but image quality precluded a definitive ‘yes’, were
381 not included in our final counts (but those images are included in the complete atlas; see Availa-
382 bility Statement for link). However, like Smith et al. (2013), we find that even over our longer
383 observation period, cloud occurrence is rare across the NPLD. In terms of seasonality, we see the
384 presence of clouds starting around L_s 10 – 20 and ending by L_s 168. This is a later end date than
385 seen in Smith et al (2013) where the last trough cloud was observed at L_s 102, but it is important
386 to note that we only observe six clouds after L_s 102, only two of which are trough-parallel. Most
387 cloud observations occurred between L_s 30 – 100, with the highest frequency between L_s 80 – 90
388 (Figure 4b). This is similar to Smith et al. (2013) (see their Figure 9), suggesting cloud patterns
389 and occurrence have overall been consistent over the last ~20 Earth years.

390 [20] Our map shows that cloud coverage across the NPLD for Mars years 26 – 35, specif-
391 ically trough-parallel clouds, is not uniform (Figure 3). Regions with the highest trough-parallel
392 cloud frequency (i.e., regions 1, 2, 3, and 4) are mainly those that contain troughs clustered together
393 centrally on the main lobe of the NPLD, while the outer regions of the deposit, especially the outer
394 lobe of Gemina Lingula (regions 5 and 7a) have about half as many trough-parallel clouds. These
395 regions do however contain troughs. Regions 6 and 7b have few to no trough-parallel clouds, but
396 also contain few troughs. Meso-scale atmospheric simulations by Smith and Spiga (2018) showed
397 that cloud counts by region roughly correlated with increases in wind speed, though cloud obser-
398 vations in regions 1-3 tended to lag peaks in wind speed. Interestingly, all the regions they looked
399 at (1-5 and 7a) had max wind speeds of ~10 m/s (though region 2 was closer to 13 m/s). It is
400 important to note that the resolution of the meso-scale model did not resolve the relatively steeper
401 high-side slopes of the troughs, which limited velocity values. Higher resolution modeling done
402 by Smith and Spiga (2018) of an individual R1 trough found that winds could reach close to 20

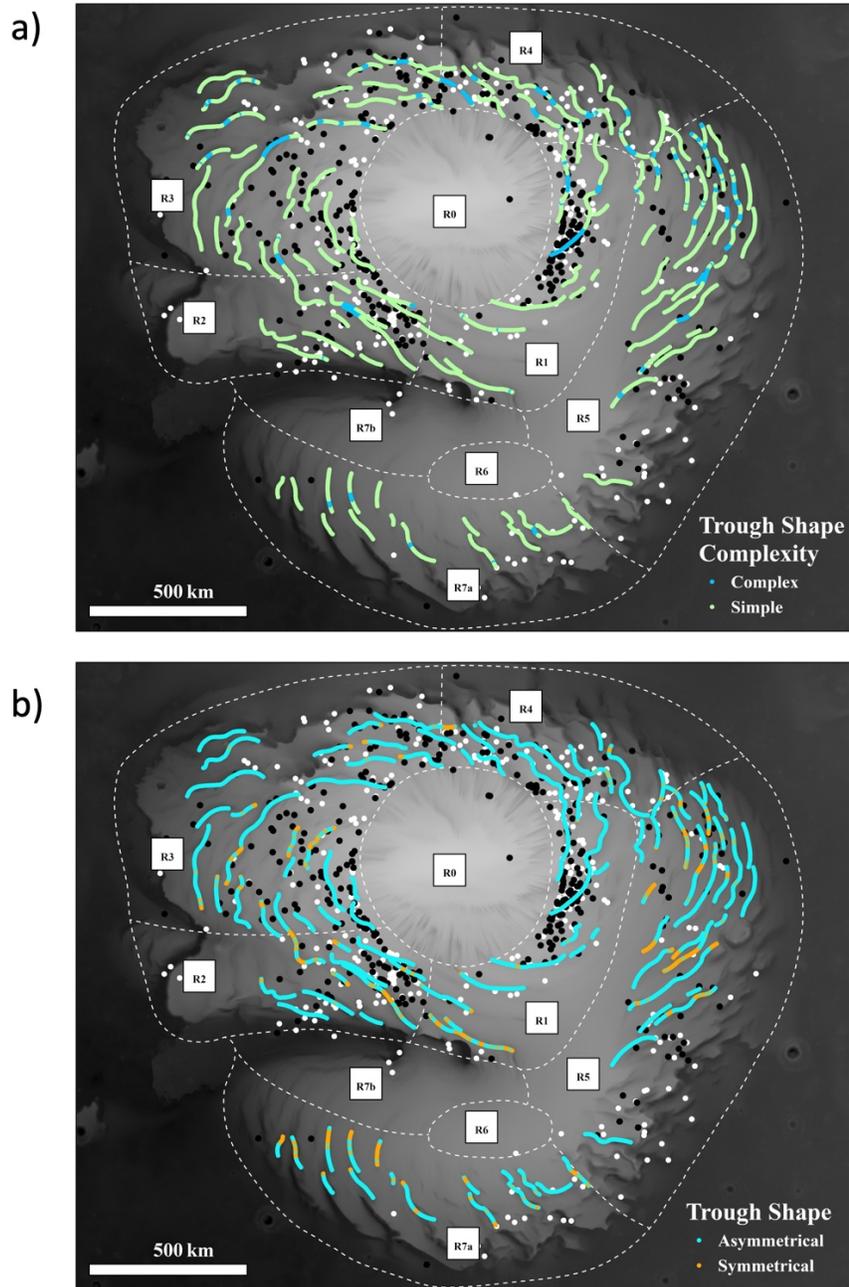
403 m/s. They suggested that cloud formation requires both strong katabatic winds, but also super sat-
404 urated water vapor, and that water vapor is limited until the seasonal CO₂ retreats poleward (after
405 $L_s \sim 80$ for the central regions). While this helps explain the temporal variability, it does not explain
406 why the distal regions of the deposit have so few clouds relative to the inner regions (assuming
407 this lack of cloud presence is not due to sampling bias in THEMIS imagery coverage). But if clouds
408 are indicators of both where winds are fast enough to lead to katabatic jumps and contain water
409 vapor (i.e., can laterally transport water/ice mass), then we would expect that modern-day lateral
410 transport is not occurring uniformly on the NPLD (and is mostly concentrated in regions 1, 2, 3
411 and 4) nor within a single trough.

412 4.2 Variations in Trough Geometry Across the NPLD

413 [21] Prior work by Smith and Holt (2015) characterized the diversity of spiral troughs
414 across the NPLD and found that while troughs had unique evolution histories, there were regional
415 surface and subsurface morphologic similarities that allowed them to be grouped into eight regions
416 (Figure 3). Most of their grouping was based on subsurface observations, including trough migra-
417 tion paths (TMPs) (estimated by tracking subsurface reflectors and their intersection with discon-
418 tinuities interpreted to be bounding surfaces created during bedform migration (Smith and Holt,
419 2010)), TMP depths, accumulation patterns, presence of “v-shaped” reflectors, which were later
420 interpreted to be buried promontories (Smith & Holt, 2015), and trough initiation slopes. Surface
421 observations mostly focused on whether layered and banded terrain was observed, trough wave-
422 length, general trough depth, the presence of central promontories (which create a “w-shaped”
423 trough cross-section), and extent of erosion. Smith and Holt (2015) classify region 1 as the arche-
424 typical region, with mostly asymmetric troughs (e.g., Figure 2a), region 2 was found to have deeper
425 troughs with occasional central promontories, and region 3 was more variable in trough depth and

426 wavelength. The surface topography of region 4 was not discussed due to past extensive erosion
427 and deposition. Troughs in region 5 were suggested to have initiated after widespread erosion and
428 hence are younger than troughs in other regions. Troughs in region 7a were also affected by exten-
429 sive erosion (like region 4), are less mature than those in other regions, and have a bedrock base
430 such that migration is forced to be horizontal. Despite these differences, it is generally stated that
431 all troughs are asymmetric in slope and elevation, having a topographic high side and low side,

432 where the high side faces approximately equatorward (e.g., Bramson et al., 2019; Howard et al.,
 433 1982; Pathare & Paige, 2005; Smith et al., 2013; Smith & Holt, 2015).



434

435 **Figure 9.** a) A map of the NPLD with trough shape complexity (simple versus complex) compared
 436 to THEMIS images with trough-parallel clouds (black circles) and general cloudiness (white

437 circles) that were identified in this study. Complex troughs included troughs with central promon-
438 tories, undular features, or both. b) Same as (a) but mapping trough wall symmetry or asymmetry.
439 Troughs were identified as symmetrical if their wall reliefs had a difference of 50 m or less.

440 [22] Our work looked at over 3000 cross-sections of troughs across the NPLD to further
441 characterize regional diversity and investigate trough shape across the deposits. While most
442 troughs have a simple u- or v-shape, there are sections of troughs that display more complex fea-
443 tures including a “w-shape” from central promontories, undulations, or a combination of both. A
444 section of “complex” trough profiles located in R1 correlates with a high trough-parallel cloud
445 presence in that location (Figure 9a), specifically to undular trough-parallel clouds (Figure S2). In
446 contrast, there are smaller sections of “complex” trough profiles in R5 that have little-to-no trough-
447 parallel clouds nearby, and sections of “complex” trough profiles in R3 and R4 that do have trough-
448 parallel clouds present, but less frequently than in R1. This variable linkage between the features
449 identified in the “complex” trough profiles, including central promontories and/or undulations, and
450 trough-parallel (often undular) clouds suggests that there may be other mechanisms driving the
451 formation of these “complex” features.

452 [23] We also aimed to investigate how ubiquitous asymmetric trough cross-sections are
453 within each region of the NPLD. This topographic asymmetry is key to the Smith et al. (2013)
454 model for lateral ice transport and cloud formation, as ablation occurs when wind accelerates down
455 the steeper high side of the trough and deposition occurs where the winds suddenly decelerate (i.e.,
456 where a hydraulic jump and cloud formation occurs). We find that troughs are generally asymmet-
457 ric across the NPLD (87% of our cross-sections were asymmetric) (Figure 8b). However, troughs
458 are not always entirely asymmetric (orange dots, Figure 9b), especially in regions 5 and 7a, though
459 portions of troughs in every region were found to have some symmetric or “v-shaped” walls (R1

460 and R4 having much fewer compared to other regions, Figure 9b). We also find that the symmetric
461 troughs in region 7a and 5 are similar in scale to those in other regions; this suggests these sym-
462 metric troughs are not simply undulations. It is also worth noting that regions with high trough
463 shape complexity are located in regions with asymmetrical troughs; no regions with strong trough
464 wall symmetry also have complex shapes. We discuss the implications for these “v-shaped” por-
465 tions of troughs on ablational and depositional processes below, but it is possible these locations
466 are surface expressions of the “v-shaped” anomalies observed in SHARAD data by Smith and Holt
467 (2010, 2015), which were interpreted to be buried central promontories (Smith & Holt, 2015).
468 While it is possible our “v-shaped” surface troughs and their subsurface “v-shaped” reflectors are
469 related, it is important to note that the “v-shaped” reflectors identified by Smith and Holt (2010,
470 2015) were found exclusively in region 1, while we find that region 1 is one of two regions with
471 little-to-no trough wall symmetry on the surface. More work comparing surface and subsurface
472 features is needed to concretely say if these “v-shaped” features are linked spatially or by formation
473 mechanism. Another possible influence on trough symmetry is the presence of small sedimentation
474 waves, which were identified on Gemina Lingula (aka regions 7a and 7b) by Heryn et al. (2014).
475 However, we also find frequent trough symmetry in region 5 and to a lesser degree in regions 2
476 and 3, suggesting that sedimentation waves are not the only explanation for trough symmetry.

477 [24] In regard to regional morphology, we did not find that one region could be clearly
478 distinguished from another based on the group of morphologic parameters investigated herein.
479 However, we did find that for certain parameters, or groups of parameters, several regions were
480 quite similar. For example, troughs in regions 1 and 5 had almost the same scale in regard to width
481 and depth (~200 m deep and ~16 km wide) and wall slopes, and as such, were statistically indis-
482 tinguishable. However, region 5 tended to have relief differences on the order of ~100 m, while

483 region 1 had a more bimodal distribution with relief differences around ~100 m and 300 m. As
484 such, based on wall asymmetry they were statistically significantly different (Table 2). We also
485 find that regions 2 and 7a generally were similar in terms of depth, width, and slope but were
486 statistically significantly different equator-facing relief and relief difference. The size of troughs,
487 including their width and depth, as well the height of their walls and their wall slopes, is likely a
488 consequence of the type and/or magnitude of modern-day surface processes that causes ablation,
489 sublimation, and deposition of ice, which is predominately driven by the atmospheric state (tem-
490 perature, pressure, and wind) as well as changing CO₂ and dust cover (e.g., Bramson et al., 2019;
491 Howard et al., 1982; Smith & Spiga, 2018). Regions that tend to be similar to one another (e.g.,
492 region 1 and 5, 2 and 7a) are geographic neighbors and thus likely experience similar insolation,
493 wind speeds and rates of atmospheric CO₂ and water vapor deposition (e.g., Smith and Spiga,
494 2018; Emmett et al., 2020; Khayat et al., 2020). However, local topographic variability (e.g., ice
495 sheet slopes, undulations in the ice, initial trough morphology, and trough spacing) likely affects
496 smaller-scale wind patterns, which determines where and how much ice and dust accumulate (e.g.,
497 Koutnik et al., 2005; Smith and Spiga, 2018), which ultimately can affect trough shape at a given
498 location. This local variability has also been observed in the subsurface (e.g., Smith & Holt, 2010;
499 2015), supporting that individual trough evolution has been variable through time and this varia-
500 bility needs to be considered when making interpretations about the linkage between NPLD stra-
501 tigraphy and climate from a given radargram or cross-section.

502 [25] Additionally, the boundaries of region 1 and 4 could be re-examined based on surficial
503 morphology. For example, the bimodal relief difference values in region 1 appear spatially distrib-
504 uted. Troughs closer to region 4 have larger relief differences and those closer to region 2 have
505 smaller relief differences. We also see that the absolute values of relief difference of troughs

506 located near region 4, but mapped within region 1, closely match those of region 4. Other factors
507 that could affect the regional distribution of trough geometry include differing climatic states in-
508 fluencing the troughs in the past as compared to the present, such as regions 5 and 7a on Gemini
509 Scopuli, which experienced a massive erosional period linked to the formation of a later generation
510 of NPLD troughs (Smith & Holt, 2015), or varying trough initiation properties, as initiation slope
511 has been seen to have a strong influence on the trough wavelengths per region (Smith & Holt,
512 2015).

513 4.3 Association Between Trough Parallel Clouds and Trough Morphology: Implications for Mod- 514 ern-Day Surface Processes

515 [26] The Smith et al. (2013) cyclic step model is currently the best accepted explanation
516 for the morphology and migration of the NPLD spiral troughs. On Earth, cyclic steps can develop
517 under net erosional conditions (e.g., Parker & Izumi, 2000), net depositional conditions (Kostic &
518 Parker, 2006) and equilibrium conditions (Taki & Parker, 2005). Smith et al. (2013) argue that the
519 NPLD is a net depositional system, as a net erosional system entrains ice and water vapor as flow
520 accelerates down the trough wall, but the load remains in suspension after the hydraulic jump
521 (Parker & Izumi, 2000). In this case, clouds would likely not be observed, and asymmetric accu-
522 mulation would not occur. The fact that Smith et al. (2013) observed trough parallel clouds in
523 conjunction with troughs that showed morphologic evidence of ice erosion and re-deposition in
524 their study areas led to the hypothesis that the troughs are constructional features across the entirety
525 of the deposit. We aimed to extend their analysis to see how ubiquitous the relationship between
526 asymmetric troughs and clouds is under modern-day climate. Based on our morphologic and sta-
527 tistical analysis, we find that areas with a high concentration of trough parallel clouds are also
528 regions with trough asymmetry (especially region 1). We also find that in most cases where

529 symmetric or “v-shaped” portions of troughs are found, trough parallel clouds are rarely present
530 (except for a portion of a trough in region 2). So broadly, our analysis supports the more local
531 findings of Howard et al. (1982) and Smith et al. (2013). As our cloud record has extended cloud
532 observations to almost 20 Earth years, and we see little change in where clouds are found, this
533 implies that these regions have been continuously active in terms of lateral ice transport. Smith et
534 al. (2013) estimate annual migration rates of ~ 20 mm/ Mars year, which would mean portions of
535 troughs in regions 1, 2, 3, and 4 have likely moved almost 0.2 m since the start of our cloud atlas,
536 which is at the edge of detection with HiRISE-derived topographic models.

537 [27] However, we did find that $\sim 13\%$ of the trough profiles we investigated were symmet-
538 ric, which means that while a net constructional cyclic step model can explain the overall evolution
539 and migration of the NPLD troughs, other processes are also likely at play. For example, insolation
540 can also remove ice from trough walls (Howard, 2000), which depending on the relative amount
541 of accumulation from the atmosphere and sublimation from insolation, could potentially result in
542 more uniform wall heights and slopes on the pole-facing and equator-facing sides of the trough.
543 There is also evidence for in-situ erosion in the form of pits and scarps across the deposit (Howard,
544 1982; Rodriguez & Tanaka, 2011; Rodriguez et al., 2021). Rodriguez et al. (2021) have theorized
545 that with an in-situ erosion model, these pits and scarps can grow and integrate overtime to form
546 troughs, similar to some karstic systems here on Earth. While this model cannot explain many of
547 the other surface and subsurface observations that have been made regarding the spiral troughs
548 (see criteria outlined in Smith et al., 2013), it is possible that in-situ erosion occurs when katabatic
549 winds are strong enough to erode, but ice deposition does not occur (similar to the net erosional
550 cyclic step model, discussed in reference to the SPLD in Smith et al. (2015)). Under these condi-
551 tions, it is possible that previously asymmetric trough walls can become more symmetric and “v-

552 shaped” (i.e., winds erode down the higher wall but there no deposition on the lower wall). Many
553 of the “v-shaped” troughs we observed are in regions 5 and 7a, which are part of Gemini Scopuli,
554 a region that experienced a massive erosional period and has younger troughs (Smith & Holt,
555 2015). This might suggest troughs there were formed by a different proportion of constructional
556 versus erosional cyclic steps or in-situ erosion compared to regions closer to the pole, or that the
557 unique erosional climate that led to these second-generation troughs also influenced their symmet-
558 ric shape. But the fact that “v-shaped” reflectors are seen in SHARAD data across the deposit
559 (including regions 1 and 2) suggest that troughs across the deposit go through periods of time
560 where changes in local wind speed, insolation, ability to entrain water/ice (i.e., sediment supply”)
561 can lead to more variable trough morphology. Understanding what controls this variability, the
562 relative proportion of erosional to depositional processes that results in a given trough profile
563 shape, and how this may have changed through time will allow us to better connect the geomor-
564 phology and stratigraphy of the spiral troughs to Martian climate processes at more local to re-
565 gional scales.

566 **5 Conclusions**

567 [28] The creation of an extended cloud atlas, covering ~18 Earth years of THEMIS VIS
568 imagery, combined with a detailed morphologic investigation of trough morphology across the
569 NPLD, allowed us to better quantify more general past observations of the NPLD (e.g., Smith et
570 al., 2013). We found that trough-parallel cloud timing and location has been consistent for ~2 dec-
571 ades, suggesting regions with clouds are continuously active in terms of modern-day change. This
572 combined with estimates of annual migration rates on the NPLD, suggests that regions with clouds

573 would have evidence of modern-day change that could potentially be directly observed with high-
574 resolution orbital data.

575 [29] We quantified the shape of NPLD troughs, using trough width, depth, wall slope and
576 relief, from ~3000 profiles. We find that trough shape is variable within a single trough, between
577 neighboring troughs, and between regions, and that trough morphology is overall not statistically
578 different between the regions identified by Smith and Holt (2015). Roughly 88% of the trough
579 cross-sections we investigated showed trough relief asymmetry and trough-parallel clouds were
580 often observed near these asymmetrical troughs (per Smith et al., 2013). The remaining troughs
581 were v-shaped and may be surface expressions of the v-shaped reflectors observed in SHARAD
582 data (Smith & Holt, 2015). The mechanism for how these v-shaped cross-sections form is outside
583 the scope of this study, but it is possible that regions of the NPLD sometimes experience erosional
584 cyclic steps (that have no ice deposition post-hydraulic jump), leading to the high-side of trough
585 walls decreased in relief over time. Our work can inform modeling studies similar to those of
586 Bramson et al. (2019) that look at trough migration using representative trough morphologies, as
587 well as comparisons between trough morphology recorded in the stratigraphy with modern-day
588 troughs. Future work will aim to investigate how varying amounts of water/ice entrainment (i.e.,
589 changes in sediment supply) affect trough wall morphology over time under critical flow condi-
590 tions.

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595 the comments and suggestions provided by our reviewers.

596 **Open Research**

597 All imagery used in this manuscript is freely available for download through the Plane-
598 tary Data System (PDS) Cartography and Imaging Sciences Node and the Caltech Murray Lab.
599 The THEMIS VIS dataset (Christensen, 2002) was used for cloud identification and classifica-
600 tion. Cross-sectional trough profiles were extracted used a HRSC and MOLA Blended 200m
601 DEM (v2) (Ferguson et al., 2018) resampled to 1000m/pixel. Figures were made with Matlab
602 version R2021b (available under a Mathworks license at mathworks.com) and Python3 scripts
603 published on GitHub (Lutz, 2023). Maps were made using ArcPro version 3.0.2 available under
604 an Esri license (available at esri.com). The cloud atlas, topographic profiles, and derived metrics
605 used to determine trough morphology across the NPLD are available at Figshare (Palucis et al.,
606 2023) with a CC by 4.0 license.

607 **References**

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Supporting Information for

**Investigating the Linkage Between Spiral Trough Morphology and Cloud Coverage
on the Martian North Polar Layered Deposits**

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Contents of this file

Figures S1 to S9

Introduction

This supporting information includes combined PDF graphs seen in the full text separately for ease of comparison of the distributions for each trough metric (Figure S1), a map showing the location of the various cloud types identified in this study (Figure S2), and histograms of the trough metrics used in this study broken down by region (Figures S3-S9).

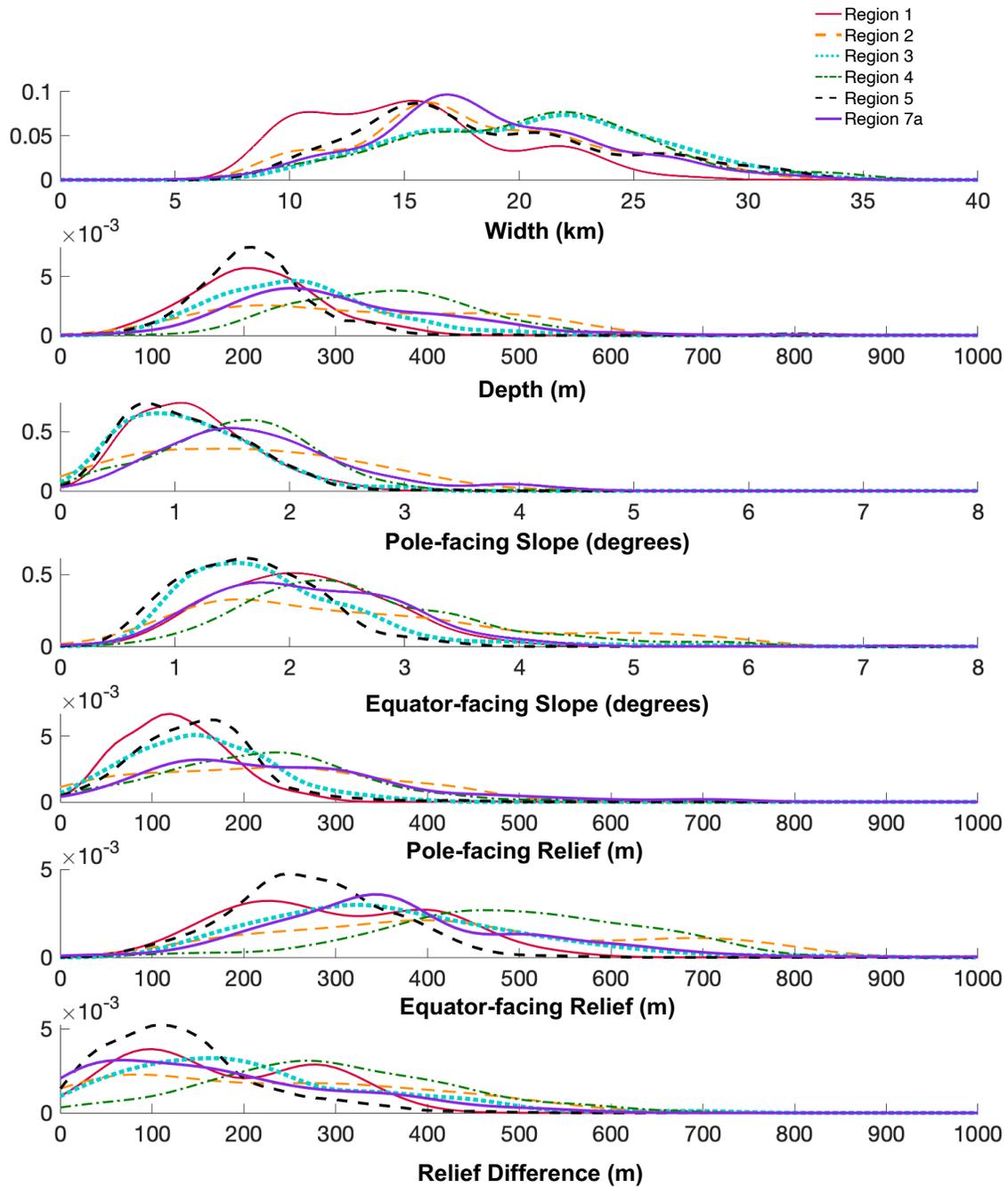


Figure S1. PDF curves of trough metric values for each region of the NPLD, broken down by metric. For histograms of raw data see Figures S3-9.

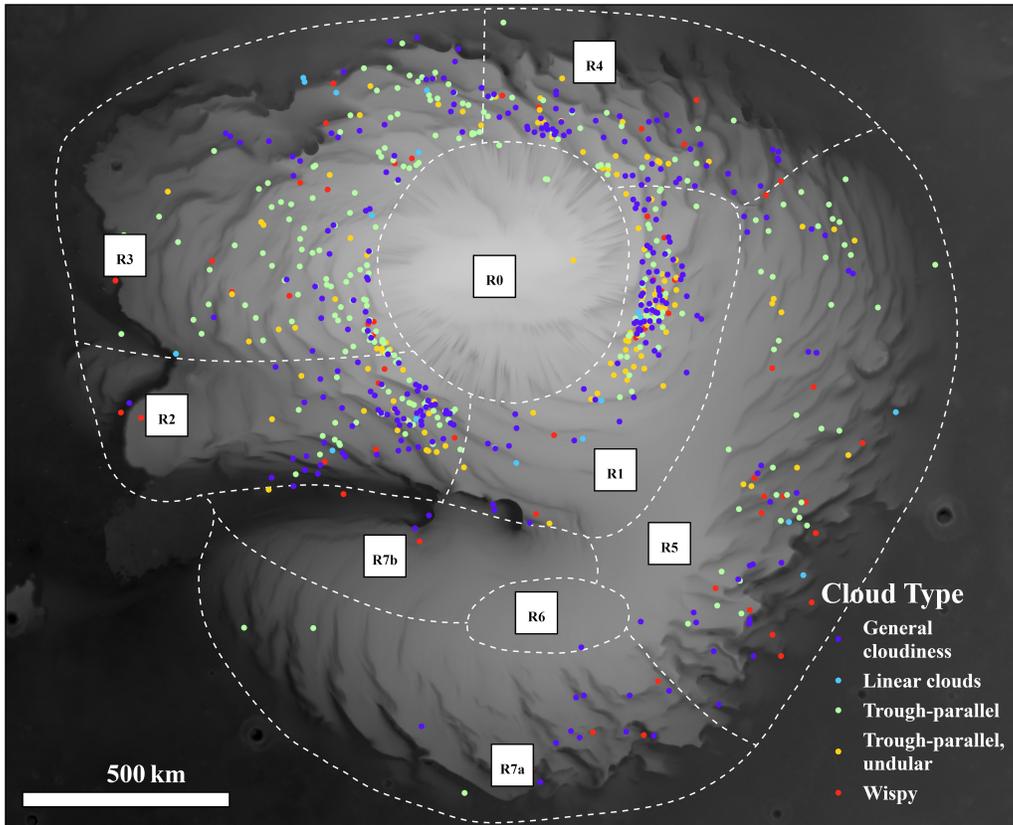


Figure S2. A map of the NPLD where THEMIS images with trough-parallel clouds (green circles), undular, trough-parallel clouds (yellow circles), linear clouds (blue circles), wispy clouds (red circles), and general cloudiness (purple circles) were identified in this study.

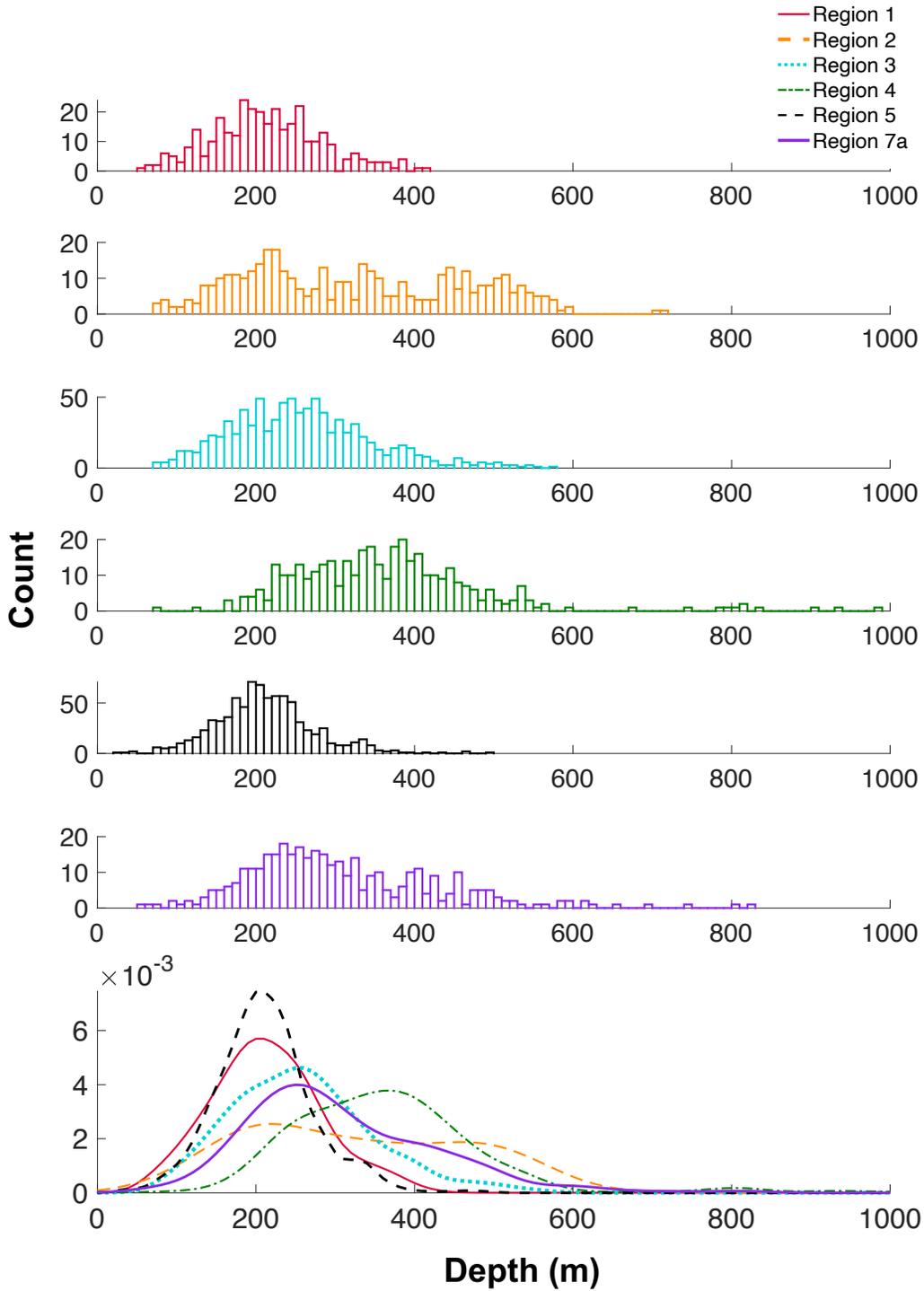


Figure S3. Histograms of trough depth data from each region, followed by probability distribution function (PDF) curves of the depth data, plotted by region. R1 is red, R2 is orange, R3 is blue, R4 is green, R5 is black, and R7a is purple. R0, R6, and R7b are not included as they have no troughs.

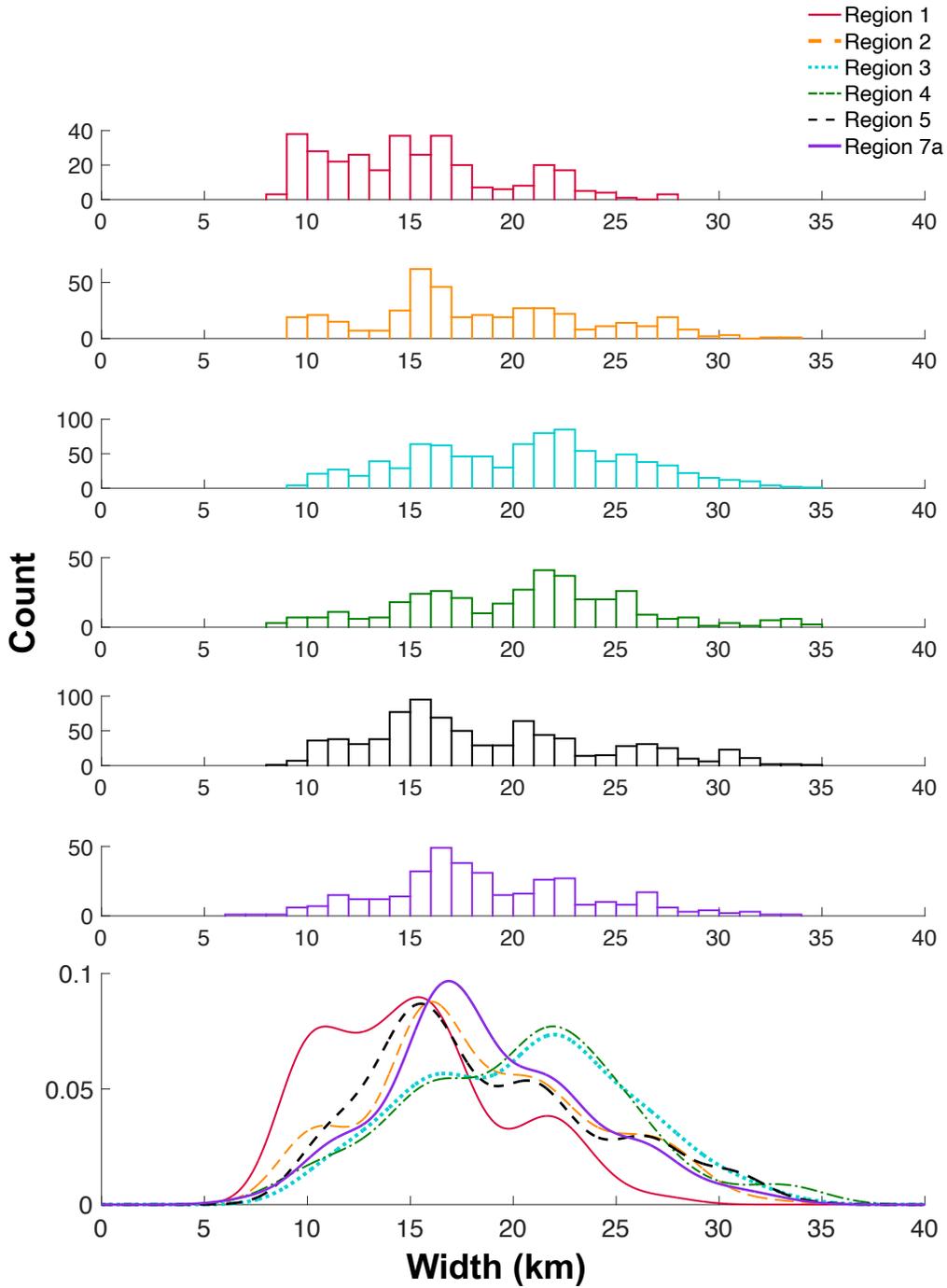


Figure S4. Histograms of trough width data from each region, followed by probability distribution function (PDF) curves of the width data, plotted by region. R1 is red, R2 is orange, R3 is blue, R4 is green, R5 is black, and R7a is purple. R0, R6, and R7b are not included as they have no troughs.

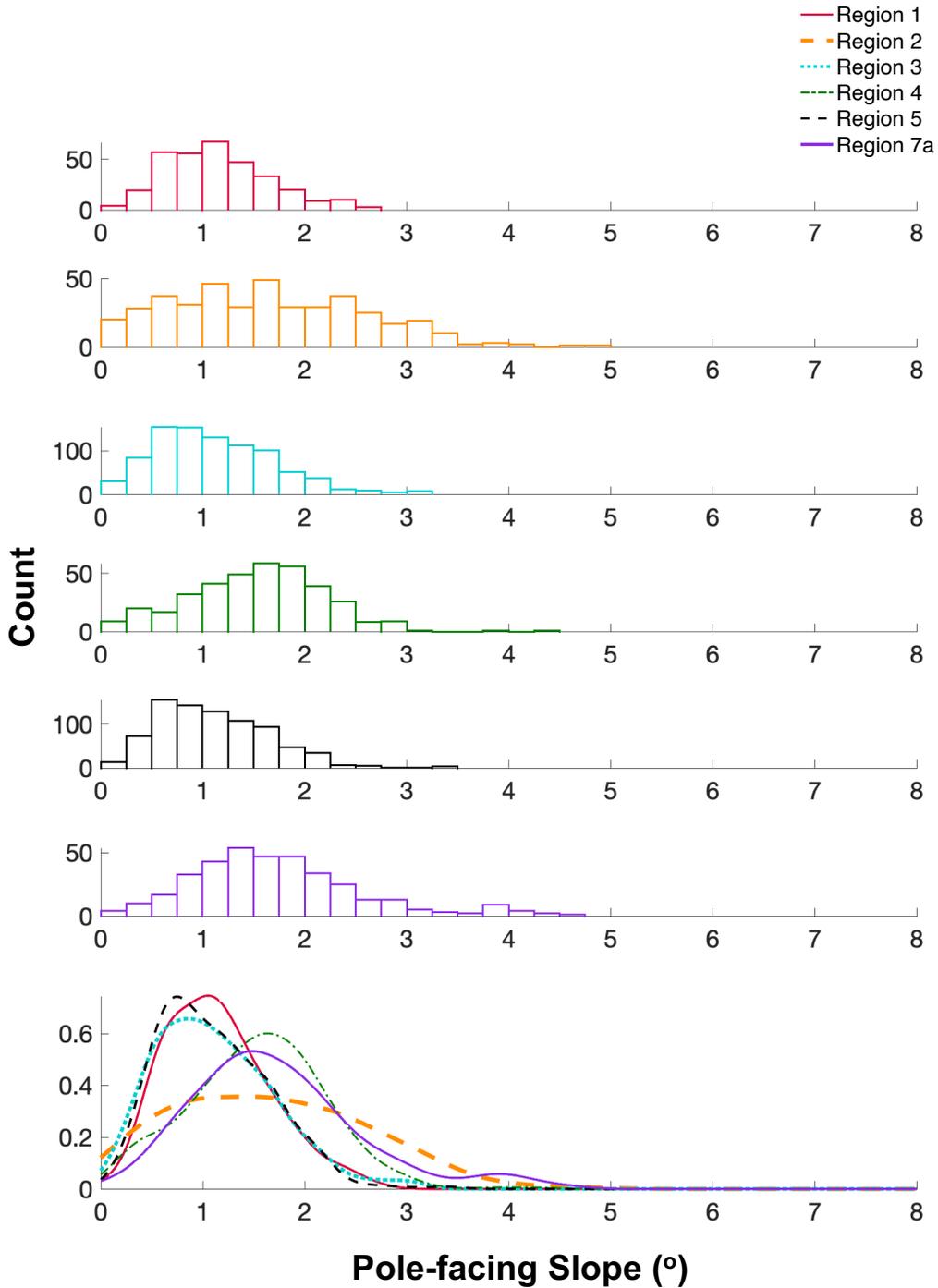


Figure S5. Histograms of trough pole-facing slope data from each region, followed by probability distribution function (PDF) curves of the pole-facing slope data, plotted by region. R1 is red, R2 is orange, R3 is blue, R4 is green, R5 is black, and R7a is purple. R0, R6, and R7b are not included as they have no troughs.

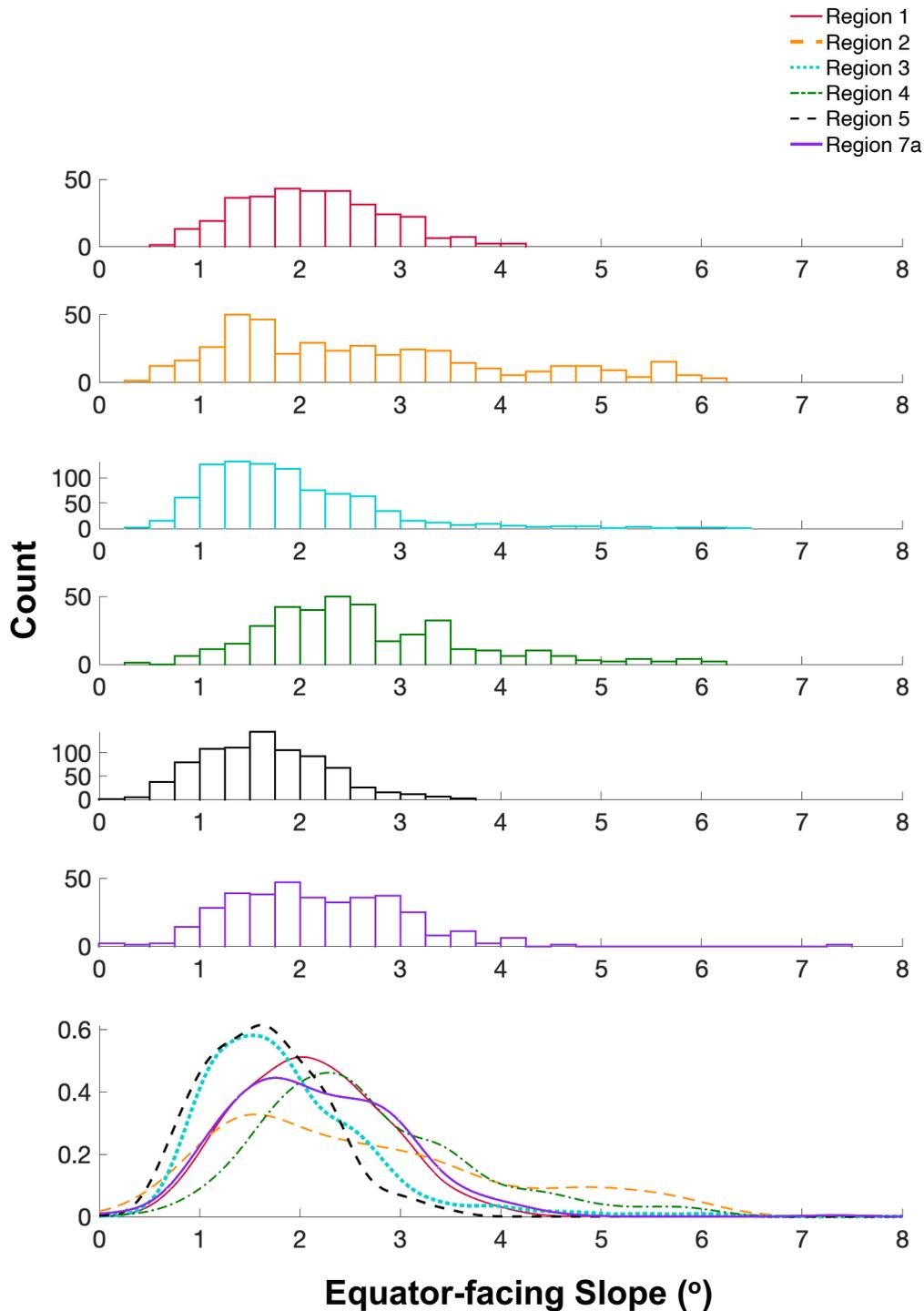


Figure S6. Histograms of trough equator-facing slope data from each region, followed by probability distribution function (PDF) curves of the equator-facing slope data, plotted by region. R1 is red, R2 is orange, R3 is blue, R4 is green, R5 is black, and R7a is purple. R0, R6, and R7b are not included as they have no troughs.

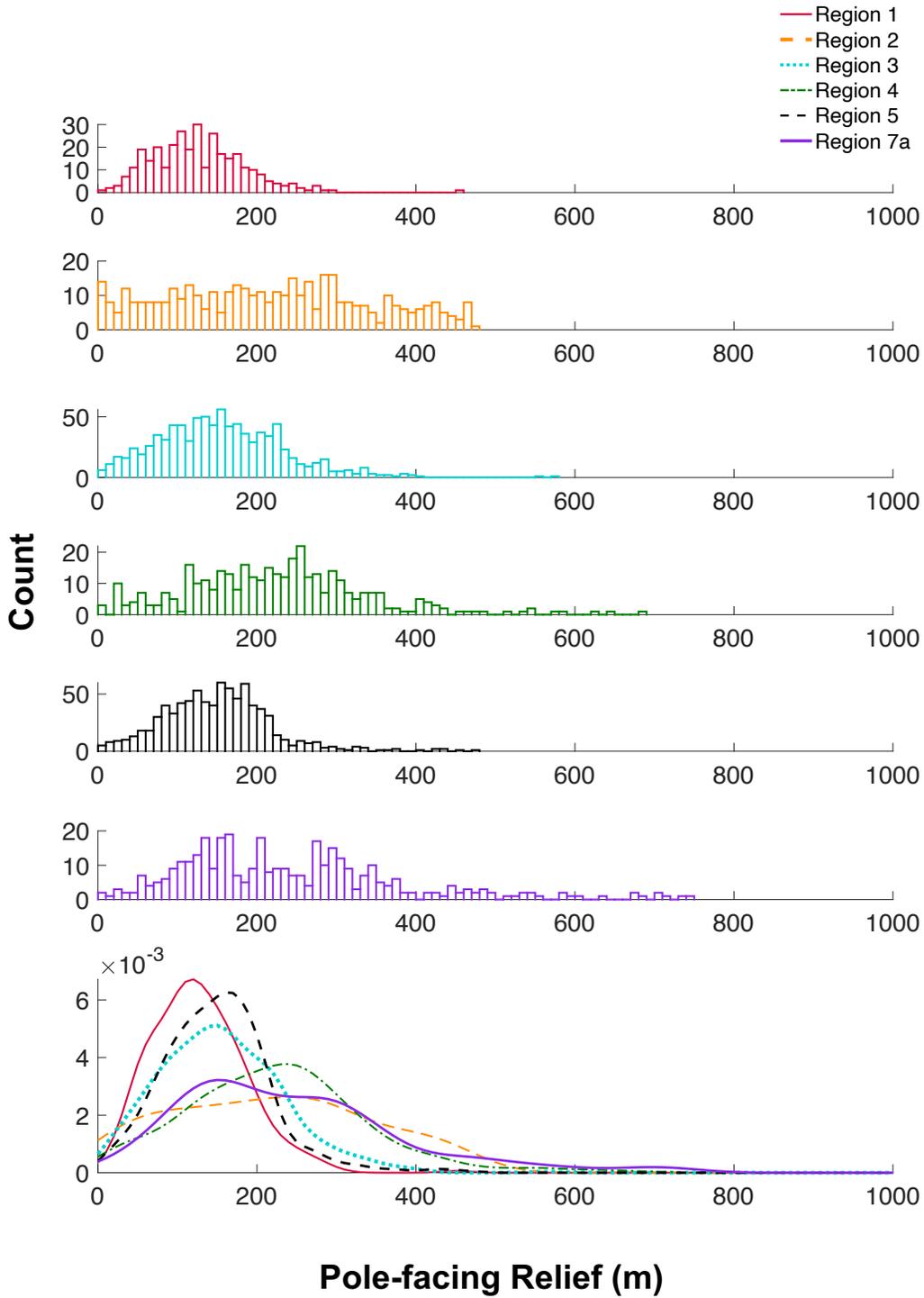


Figure S7. Histograms of trough pole-facing relief data from each region, followed by probability distribution function (PDF) curves of the pole-facing relief data, plotted by region. R1 is red, R2 is orange, R3 is blue, R4 is green, R5 is black, and R7a is purple. R0, R6, and R7b are not included as they have no troughs.

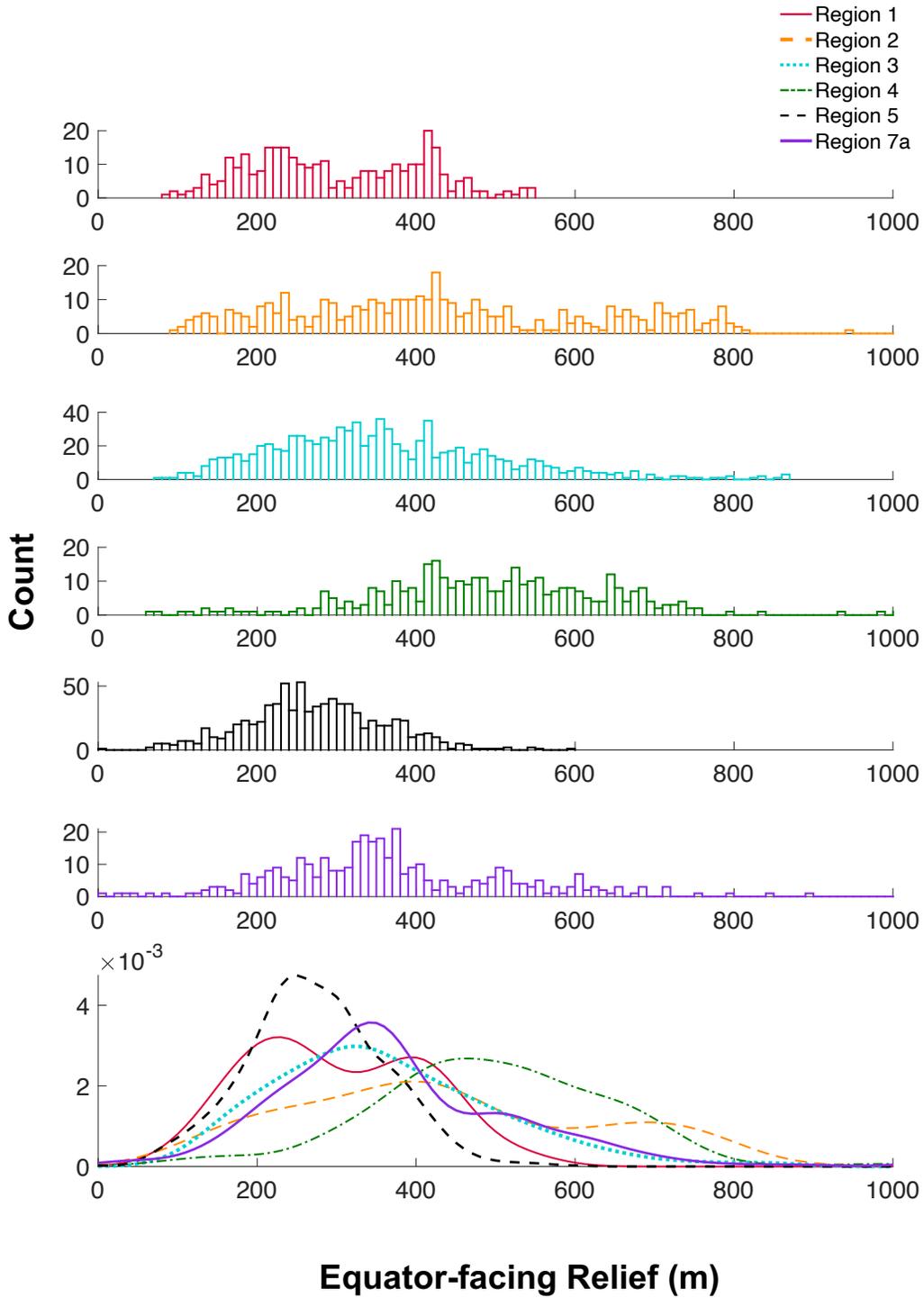


Figure S8. Histograms of trough equator-facing relief data from each region, followed by probability distribution function (PDF) curves of the equator-facing relief data, plotted by region. R1 is red, R2 is orange, R3 is blue, R4 is green, R5 is black, and R7a is purple. R0, R6, and R7b are not included as they have no troughs.

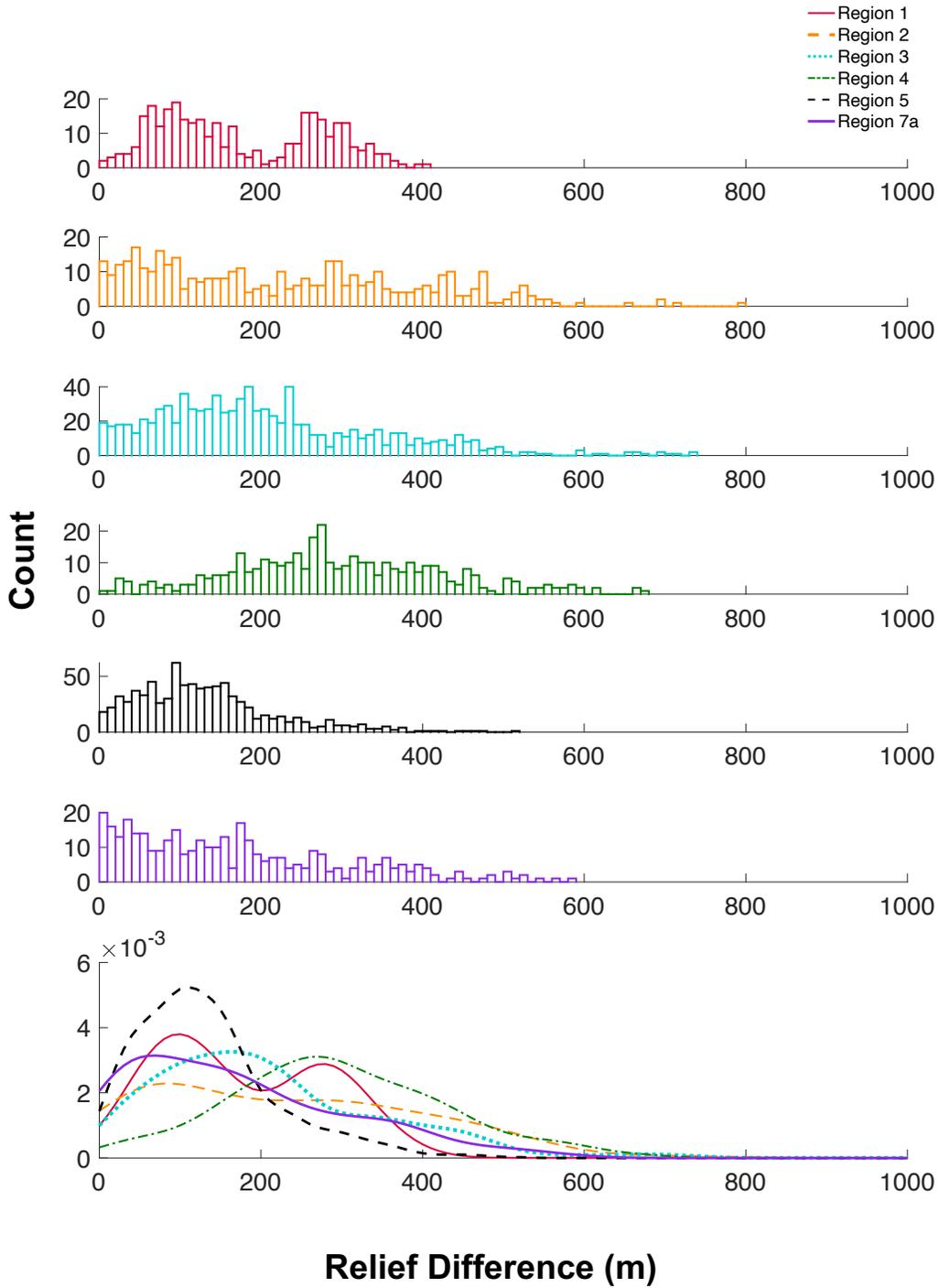


Figure S9. Histograms of trough wall relief difference data from each region, followed by probability distribution function (PDF) curves of the relief difference data, plotted by region. R1 is red, R2 is orange, R3 is blue, R4 is green, R5 is black, and R7a is purple. R0, R6, and R7b are not included as they have no troughs.