

1 **Constraining the mechanisms of aeolian bedform formation on**
2 **Mars through a global morphometric survey**

3
4 **David A. Vaz¹, Simone Silvestro^{2,3}, Matthew Chojnacki⁴ and David C. A. Silva¹**

5 ¹ Centre for Earth and Space Research of the University of Coimbra, Observatório Geofísico e
6 Astronómico da Universidade de Coimbra, Coimbra, Portugal.

7 ² INAF Osservatorio Astronomico di Capodimonte, Napoli, Italia.

8 ³ SETI Institute, Carl Sagan Center, Mountain View, CA, USA.

9 ⁴ Planetary Science Institute, Lakewood, CO, USA.

10
11 Corresponding author: David Vaz (davidvaz@uc.pt)

12
13 **Key Points:**

- 14 • We present a global morphometric survey of aeolian bedforms on Mars and assess the
15 mechanisms that may control their size
- 16 • Bedforms within the high elevation Tharsis region form a distinct group, attributed here
17 to different sediment and transport conditions
- 18 • We confirm the existence of a robust relation between wavelength and atmospheric
19 density, which is consistent with a fluid-drag mechanism
- 20

21 Abstract

22 Aeolian processes on Mars form a distinct class of meter-scale ripples, whose mechanisms of
23 formation are debated. We present a global morphometric survey of bedforms on Mars, adding
24 relevant observational constraints to the ongoing debate. We show that the bedforms located in
25 the Tharsis region form a distinct group, not akin to the large dark-toned ripples which cover
26 dune fields elsewhere on the planet. The relation between wavelength and atmospheric density
27 derived from the new data is consistent with the predictions of a wind-drag mechanism, favoring
28 the model that uses a saltation saturation length. Regardless of the mechanism that limits the size
29 of bedforms, these results confirm the existence of a robust relationship between the wavelength
30 of large ripples and atmospheric density (ripples spacings increases with decreasing atmospheric
31 density). This provides further support to the interpretation of paleoatmospheric conditions on
32 Mars through the analysis of its aeolian sedimentary record.

33

34 Plain Language Summary

35 The winds that shape the surface of Mars form two distinct scales of aeolian ripples, which
36 coexist and evolve over martian dunes. The larger ripples (with spacing between crests between
37 1-5 m) are enigmatic, as the mechanisms that control their equilibrium size are not fully
38 understood. In this study we provide new observational data, which we use to assess different
39 models that predict a dependence of bedform wavelength with atmospheric density. This new
40 dataset shows that there are more than one population of meter-scale bedforms, with the ones
41 located around the Tharsis volcanos being significantly different from the ones that cover dark
42 dunes. We found a good agreement with the predictions of the wind-drag model, suggesting that
43 the size of the large ripples is controlled by an aerodynamic mechanism. Most importantly, we
44 confirm the existence of a global relation between wavelength and atmospheric density (ripples
45 spacings increases with decreasing atmospheric density). This provides further support to the
46 interpretation of paleoatmospheric conditions on Mars, as this relation can be applied to infer
47 past atmospheric densities from the sedimentary record.

48

49 **1 Introduction**

50 Martian dark dunes are covered by large ripple-like bedforms which are actively migrating
51 under present-day atmospheric conditions (Bridges et al., 2012; Silvestro et al., 2010). These are
52 metric-scale bedforms (~1-5 m spacing between crests, ~5-40 cm high) which can have
53 symmetrical or asymmetrical profiles and sinuous or straight crests. On terrestrial aeolian
54 environments with well-sorted sediments there are no obvious analogue bedforms in terms of
55 scale, morphometry and dynamics (Lapotre et al., 2018; Silvestro et al., 2016; Vaz et al., 2017).
56 Most notably, the meter-scale bedform are overlaid by centimeter-scale ripples, similar in scale
57 and dynamics to impact ripples (Bridges et al., 2012; Lapotre et al., 2016; Weitz et al., 2018). The
58 coexistence to these two different scales of bedforms raised several questions. Namely, why do we
59 have two scales of ripples on Mars and what are the mechanisms that control their sizes?

60 To explain orbital and ground-based observations of widespread aeolian activity (Baker et
61 al., 2022; Bridges et al., 2012; Silvestro et al., 2010, 2013) transient low-flux transport regimes,
62 that occur between impact threshold and fluid threshold speeds, were invoked (Andreotti et al.,
63 2021; Baker et al., 2018; Lapotre et al., 2018; Sullivan & Kok, 2017; Swann et al., 2020). Recent
64 in situ observations by the Curiosity rover at Gale crater demonstrate that intermittent saltation is
65 taking place, contributing to the migration of centimeter-scale ripples (Baker et al., 2022; Sullivan
66 et al., 2022). In addition, wind tunnel experiments suggest that the size of impact ripples does not
67 vary significantly with atmospheric density, maintaining their characteristic centimeter scale even
68 in the low density conditions that exist on the surface of Mars (Andreotti et al., 2021). Therefore,
69 all evidence shows that the size of centimeter scale ripples on Mars is controlled by the same
70 impact-splash mechanism that produces terrestrial aeolian impact ripples.

71 In contrast, two hypotheses have been proposed to explain the origin of the meter-scale
72 ripples. They have been interpreted: a) as arising from a hydrodynamic instability i.e., they are
73 analogous to fluid drag ripples typically found on terrestrial subaqueous environments (Duran
74 Vinent et al., 2019; Lapotre et al., 2016, 2021); or b) as forming from the same impact-splash
75 mechanism as terrestrial aeolian ripples (Sullivan et al., 2020; Sullivan & Kok, 2017). In the first
76 hypothesis, the equilibrium wavelength of the large ripples is limited by a hydrodynamic anomaly
77 (Duran Vinent et al., 2019; Lapotre et al., 2016), while in the second case ripple height (and
78 consequently their wavelength) is controlled by the wind dynamic pressure at the bedforms crests,
79 which is lower on Mars and would allow the growth of the bedforms (Sullivan et al., 2020). Lapotre

80 et al. (2016, 2021) argued that there is a clear wavelength gap between the two types of bedforms,
 81 inferring that two different mechanisms are limiting the size of the bedforms (impact-splash for
 82 the centimeter-scale ripples and fluid-drag for the meter-scale bedforms). In contrast, Sullivan et
 83 al. (2022) reported a continuum distribution of superimposed ripple wavelengths observed by the
 84 Curiosity rover at the “Sands of Forvie” sand sheet. They also reported the existence of
 85 granulometric segregation between the troughs and crests of large ripples (the same was reported
 86 in other areas by Gough et al., 2021) with coarser grains preferentially located on the crests of the
 87 larger bedforms. They interpreted these two characteristics as evidence that the meter-scale ripples
 88 are impact ripples rather than fluid-drag bedforms.

89 An important aspect of the debate about the mechanism that sets the size of large ripples is
 90 the near-inverse relation observed between wavelength and atmospheric density at a global scale.
 91 This relation was initially hinted at by Lorenz et al. (2014) for the bedforms located across the
 92 high elevation Tharsis region, while Lapotre et al. (2016) extended the number of surveyed areas,
 93 focusing on sites where dark dunes are present. Based on this compilation, Lapotre et al. (2016)
 94 argued that the observed decrease in ripple wavelength with increasing atmospheric density is
 95 consistent with a fluid-drag origin. A view not shared by Lorenz (2020), which highlighted the
 96 different gradient of the model predictions and observational data (see Fig. 2 in Lorenz, 2020).
 97 Lapotre et al. (2021) revisited the same dataset proposing that when a saltation saturation length
 98 formulation is adopted (Duran Vinent et al., 2019), the fluid-drag mechanism provides a better fit
 99 to the data, particularly to the bedforms analyzed outside Tharsis.

100 Drag ripples wavelength scales according to $\lambda \approx \frac{\left(\frac{\mu}{\rho_f}\right)^{2/3} D^{1/6}}{(Rg)^{1/6} u_*^{1/3}}$ (Lapotre et al., 2017), where μ is
 101 the dynamic viscosity, ρ_f is the fluid density, D is grain diameter, g is the gravity acceleration and
 102 R is the submerged reduced density of the sediment $\left(\frac{\rho_s - \rho_f}{\rho_f}\right)$. This relation predicts that bedform
 103 wavelength is strongly dependent on $\rho_f^{-2/3}$. The mechanisms that set the wavelength of impact
 104 ripples are less understood. Wind tunnel experiments show that the saturation wavelength on well
 105 sorted sediments increases linearly with friction velocity (Andreotti et al., 2006; Cheng et al., 2018;
 106 Rasmussen et al., 2015), and is thought to be limited by the height of the ripples (Bagnold, 1954;
 107 Manukyan & Prigozhin, 2009). Yet, in less well sorted sediments coarser particles form an armor
 108 layer on the crests, causing ripples to increase in height and consequently in wavelength (Sharp,

109 1963). Sullivan et al. (2020) argue that the wind dynamic pressure $WDP = \frac{1}{2}\rho_f u^2$ (u is the wind
110 velocity) controls ripples height, with higher dynamic pressures removing particles from the crests
111 and precluding the growth of the bedforms. Therefore, higher WDP should generate smaller
112 ripples. In this case, if we assume a constant wind velocity the wavelength of impact ripples scales
113 with $1/\rho_f$. Note that this assumption (constant wind speed at a global scale) may be problematic,
114 as according to the equation WDP may be relatively more influenced by wind velocity than by
115 density variations, which is the only factor addressed in previous studies as well as in this work.
116 Nevertheless, both theories suggest an increase in wavelength when atmospheric density
117 decreases.

118 Other questions not entirely settled in previous studies regard the nature of the bedforms
119 located in the Tharsis region. Lapotre et al. (2016) noticed the morphologic and albedo differences
120 between the dark-toned ripples covering dunes and Tharsis bedforms. Nevertheless, they merged
121 the two datasets to fit their wind-drag model, while in later works Tharsis and non-Tharsis
122 bedforms were analyzed separately (Lapotre et al., 2021; Lorenz, 2020).

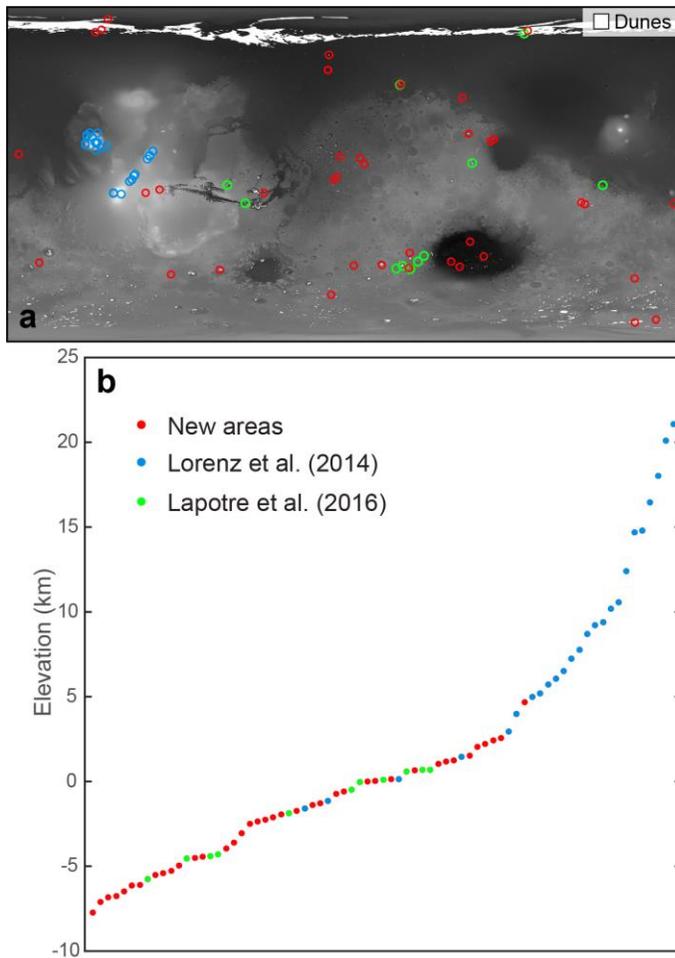
123 Here we focus on these unresolved issues, reviewing and expanding the observational
124 dataset, analyzing the consistency of measurements, and testing the models that predict the size of
125 large ripples on Mars as a function of atmospheric density.

126

127 **2 Data and methodology**

128 We use High-Resolution Imaging Science Experiment (HiRISE) images (0.25-0.5 m/pix,
129 McEwen et al., 2007) to perform a global scale mapping and wavelength survey of aeolian
130 bedforms. Our survey cover the same 25 areas located in the Tharsis regions and analyzed by
131 Lorenz et al. (2014), as well as the 11 areas reported in Lapotre et al. (2016) (Fig. 1). Furthermore,
132 we expand the elevation coverage including 39 new areas where meter-scale bedforms are present
133 covering dark-toned dunes (Supporting information S1 - section 1, Fig. S1 and Table S1).

134



135

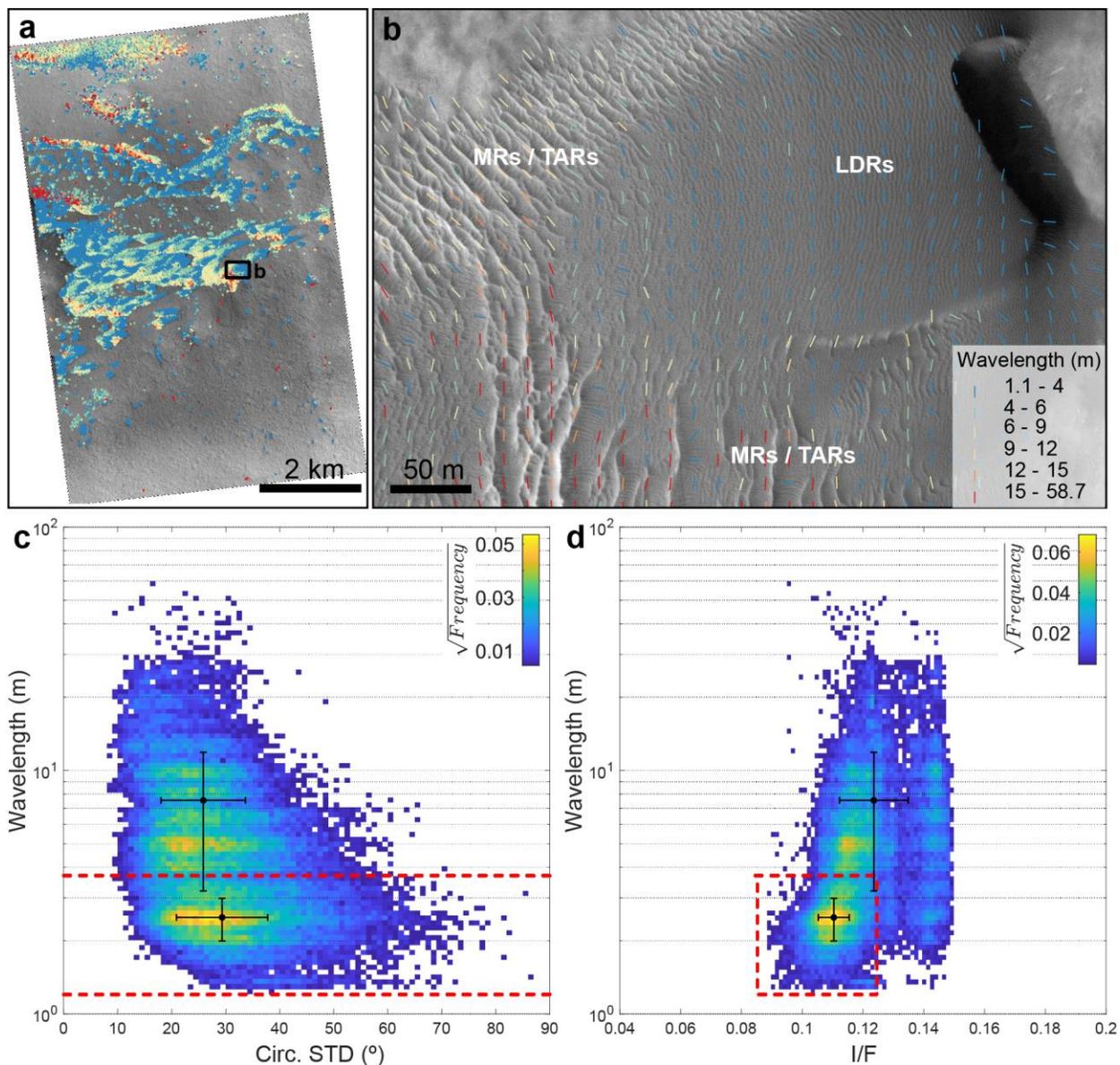
136 **Figure 1.** Location (a) and elevation distribution (b) of the 75 sites surveyed in this study. We
 137 analyzed the same 25 areas of Lorenz et al. (2014) as well as the 11 dark-tone dune sites previously
 138 analyzed by Lapotre et al. (2016). Our survey improves the spatial coverage, extends the range of
 139 surveyed elevations and provides a more continuous elevation sampling. A global dune catalog
 140 (Fenton, 2020; Hayward et al., 2014) is shown overlaying MOLA elevation data.

141

142 Previous surveys relied on the discrete manual measurements of crest-to-crest distances in
 143 randomly selected points (Lapotre et al., 2016; Lorenz et al., 2014). Here we applied a set of image
 144 processing and machine learning techniques which allow the mass automatic mapping of bedforms
 145 and the accurate measurement of their wavelengths (Fig. 2). We adapted the 2D Fast Fourier
 146 Transform approach introduced by Voulgaris and Morin (2008), implementing a multiscale
 147 scheme coupled with neural networks. This method allows the mapping and characterization of

148 large ripples and transverse aeolian ridges (TARs) in a wide range of spatial scales and surface
 149 settings. See Supporting information S1 - section 2 for a in depth description of the method.

150



151
 152 **Figure 2.** Wavelength survey of aeolian bedforms on Lyot crater (ESP_055318_2290, area 26 in
 153 Table S1). a) The applied method allows the full mapping and wavelength characterization of
 154 aeolian bedforms. b) Detailed view of the wavelength and trend of the mapped bedforms: large
 155 dark-toned ripples (LDRs) cover a barchan dune and have a spacing between crests of less than 4
 156 m; megaripples (MRs) and transverse aeolian ridges (TARs) present higher albedos, higher
 157 wavelengths and are overlaid by the dune darker sediments. c and d) 2D histograms showing the

158 distribution of wavelength, circular standard deviation and albedo (I/F), a square root stretch is
159 used to highlight secondary peaks. Red dashed lines correspond to the wavelength and albedo
160 thresholds used to segment two bedform classes. The black dots and lines represent the computed
161 averages and 1σ intervals.

162
163 Previous studies analyzed the relation between the average wavelength and atmospheric
164 density at the surface, focusing on large ripples and TARs. To comply with this framework, we
165 segment the mapped bedforms in two classes: a) large dark-toned ripples and b) a second class that
166 comprises megaripples and TARs. Wavelength and relative grain size were proposed to be key
167 parameters to discriminate different types of aeolian bedforms on Mars (Day & Zimelman, 2021).
168 We use albedo as a proxy for grain size, as it is usually assumed to be related to dust coating and/or
169 to the presence of coarser particles (Sullivan et al., 2020). We examine the wavelength and albedo
170 distributions using 2D histograms and we define threshold values that allow the partition of the
171 mapping results, so that summary statistics can be computed for each class (see Supporting
172 information S1 - section 3 for examples and Supporting information S2 for global results).

173 To evaluate the mechanisms that set the size of large ripples on Mars we test which model
174 best describes the wavelength vs. atmospheric density relation observed in our dataset. We tested
175 three models (refer to Supporting information S1 - section 5 for details): a) the wind-drag model
176 of Lapotre et al. (2016), where the saturation length scale is approximated as that of fluvial
177 bedload, b) a modified version of the same scaling, which instead uses a saturation length scale for
178 aeolian saltation (Duran Vinent et al., 2019; Lapotre et al., 2021), and c) a generic inverse linear
179 dependence between wavelength and atmospheric density (as proposed by Lorenz et al., 2014).
180 We fit power laws and linear models to facilitate the comparison between our measurements and
181 the models' predictions.

182

183 **4 Results and discussion**

184 Bedforms spaced between 1 to 100 m were mapped over a total area of ~ 2200 km²
185 (Supporting information S2). The applied method correctly identifies the location of bedforms
186 (93.7% of overall accuracy) and robustly measures their wavelength (we estimate a confidence
187 interval of $\pm 12\%$, Supporting information S1 - section 2). When comparing our data with previous

188 surveys, we found a good agreement with large ripple measurements reported by Lapotre et al.
189 (2016), which on average differ by 4%. Yet, the averages for the larger bedforms (megaripples
190 and TARs) reported in the same study are severely underestimated by 84%, which we attribute to
191 a possible under sampling. To assess the wavelength of these larger bedforms Lapotre et al. (2016)
192 collected on average of 46 wavelength measurements on each site. This number of randomly
193 located measurements may not be enough to characterize these populations, as they cover a small
194 percentage of the mapped areas and form scattered patches of bedforms with variable wavelengths.

195 Our results for the Tharsis sites (which represent $\sim 2/3$ of the data analyzed in previous
196 studies) show that Lorenz et al. (2014) values are systematically underestimated: on average they
197 are 73% lower than the values obtained in this study (Fig. S10 and S11; Supporting information
198 S1 - section 4). Indeed, some cited measurements there (e.g., 0.5-1.1 m) are dubious at best given
199 HiRISE resolution (0.25 m/pix). The causes for this large disparity are less clear, nevertheless we
200 note that in this case the measurement locations were not randomized, and that in some of the areas
201 the spatial distribution of the bedforms is not uniform. These two factors may complicate the
202 obtention of representative values from a few tens of scattered measurements.

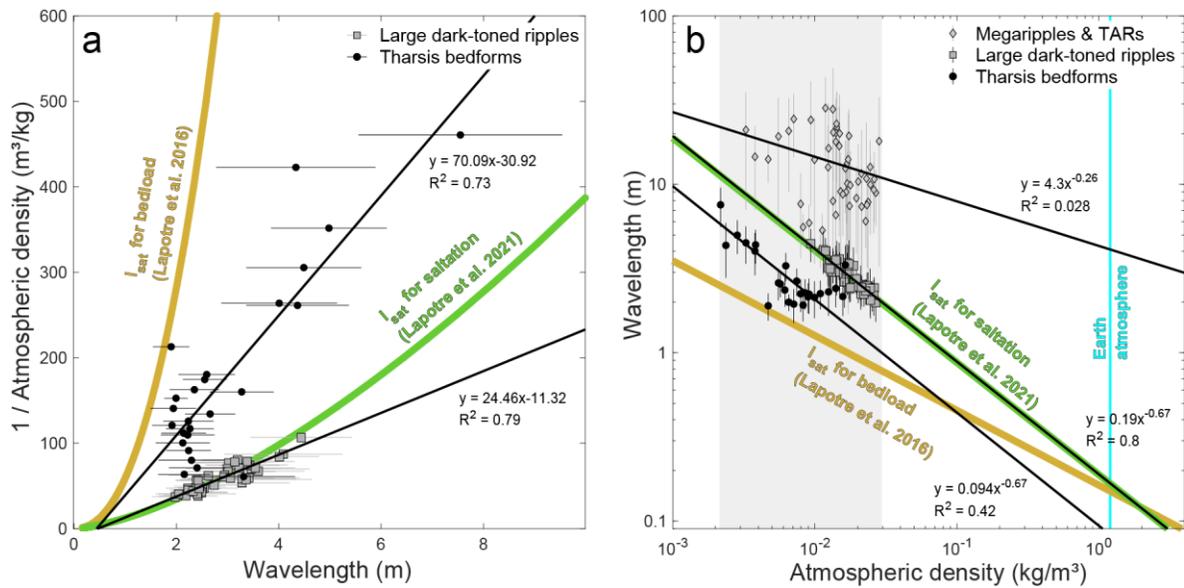
203 Other potential sources of uncertainty are the elevation values reported for each site, which
204 are used to derive the atmospheric pressure. We sampled the MOLA elevations at the centroid
205 point of the largest bedform patch mapped in each area. However, previous works do not refer the
206 sampling scheme or location where elevation values were collected. Therefore, in areas where the
207 HiRISE footprints cover regions with higher elevation gradients (mainly in the Tharsis region) we
208 can have elevation differences between our values and previous surveys of more than 2 km. This
209 happens in four of the areas analyzed by Lorenz et al. (2014) (Fig. S11b).

210 We found several lines of evidence which support that Tharsis bedforms form a distinct
211 population, apart from the large dark-toned ripples found elsewhere on Mars: a) as noted by
212 Lapotre et al. (2021), we found that Tharsis bedforms have higher albedos (Fig. S12); b) we found
213 that they have distinct thermal inertia (Putzig and Mellon, 2007) and dust cover index signatures
214 (Ruff and Christensen, 2002), denoting lower thermal inertias (possibly associated with finer
215 materials) and higher dust content/coverage (Fig. S13); c) as noted by others, Tharsis bedforms
216 form unique patterns (Fig. S14) such as honeycomb or reticulate patterns (Bridges et al., 2010;
217 Lorenz et al., 2014); and d) are in most cases associated with extensive mantling units, while large
218 ripples outside Tharsis are typically found overlaying dark dunes (see Supporting information S1

219 - section 5 for details). These distinctive characteristics suggest that the two sets of bedforms
 220 should be considered separately when evaluating bedform-formation mechanisms.

221 The compiled data confirms the existence of a decrease of wavelength with increasing
 222 atmospheric density for the large dark-toned ripples (Fig. 3). Only five areas (~7%) deviate from
 223 this general tendency (Supporting information S1 - section 5 and Fig. S15), corresponding to cases
 224 where: a) sand sheets occupy a significant percentage of the mapped areas, suggesting the presence
 225 of coarse and/or poorly sorted sediments; and b) where dust devil tracks are visible covering the
 226 bedforms, suggesting limited migration/activity. These outliers are not included in the fits done to
 227 evaluate the proposed models, but their existence highlights two points: the accuracy and
 228 consistency of the measurements and the need to select comparable dune settings, as differences
 229 in grain size and sorting influence the wavelength of the bedforms.

230



231

232 **Figure 3.** Relation between bedforms wavelength and Martian atmospheric density. The same data
 233 is shown in two different plots: a) highlighting the linear inverse relation proposed by Lorenz et
 234 al. (2014) and b) comparing with the models proposed by Lapotre et al. (2016; 2021), the gray area
 235 represents the maximum range of atmospheric densities on Mars while the cyan line represents the
 236 density of Earth's atmosphere. Black lines represent the best fitted models for each dataset,
 237 computed using the average wavelengths for each site (linear models in a) and power laws in b);
 238 the R^2 values in b) were computed in the log space). The golden line represents Lapotre et al.
 239 (2016) empirical relationship where transport saturation length is taken as that of fluvial bedload,

240 while the green line corresponds to a transport saturation length for aeolian saltation (Lapotre et
241 al., 2021). A similar plot that includes the datasets used in previous studies is shown in Fig. S19.

242

243 The model obtained by fitting previous datasets which takes into account the bedload
244 transport saturation length (Lapotre et al., 2016) predicts significantly lower wavelengths and a
245 different scaling to the one we derived from our dataset. Conversely, our data for the dark-toned
246 large ripples overlaps the predictions of the wind-drag model that uses the saltation transport
247 saturation length, with a best fitted power law with $\sim 2/3$ scaling.

248 Tharsis data presents higher scattering, particularly for lower wavelengths where data
249 points seem to converge towards the dark-toned ripple dataset. Due to the discrepancies found
250 between our results and those of Lorenz et al. (2014), we note that the Tharsis data compiled in
251 this study does not overlap or follow a similar scaling to the wind-drag model that considers a
252 bedload transport saturation length (Fig. 3 and S19). Instead, the best fitted power law ($R^2=0.42$)
253 has the same scaling ($\sim 2/3$) of the model that uses the saltation transport saturation length.

254 The compiled data suggests that the mechanism that limits the size of large ripples on Mars
255 is dependent on the atmospheric density. Overall, we observe that all our data are bounded by the
256 two saturation length scaling laws, supporting the hypothesis that the equilibrium size of large
257 martian ripples is controlled by an aerodynamic mechanism. The scaling laws for saturation length
258 arise from idealized representations of transport in unimodal sediments. As previously discussed,
259 the grain size distribution of the sediments on the Tharsis bedforms is probably more complex,
260 which may contribute to the observed differences between Tharsis and non-Tharsis bedforms.

261 Even so, in accordance with previous studies (Lorenz, 2020; Lorenz et al., 2014) we notice
262 that linear functions (which imply that
263 $\lambda \propto 1/\rho_f$) also provide robust fits to the data ($R^2=0.79$ and 0.73 for the dark large ripples and
264 Tharsis bedforms, respectively). In the case of the large ripples, both inverse and power law
265 functions explain $\sim 80\%$ of the variance. This means that, strictly from a numeric point of view,
266 we cannot discriminate what is the best model to fit the data. As previously mentioned, to fully
267 test the impact ripple hypothesis we would need to consider the wind velocities at each site,
268 something that could be done using climate model predictions.

269 Finally, the wavelengths of the larger bedforms (megaripples and TARs) present a large
270 dispersion (Fig. 3B), not showing an obvious relation with any of the scaling laws. Linear or power

271 law models do not produce a meaningful fit to the data ($R^2=0.03$). This suggests that at a global
272 scale these bedforms do not form a homogeneous set and are probably not representative of the
273 same boundary conditions (i.e., they likely formed with different grain size distributions, or under
274 differing atmospheric conditions). Nonetheless, we cannot exclude the possibility that including
275 TARs and megaripples in a same class may be flawed, especially since different degrees of
276 mobility under present day winds have been described for the two sets of bedforms (Chojnacki et
277 al., 2021; Silvestro et al., 2020).

278 For the dark-toned large ripples the degree of agreement between the global measurements
279 and the predictions of the scaling relationship of Lapotre et al. (2021) (where saturation length is
280 taken as that of aeolian saltation) is remarkable. Particularly if we consider that we are using a
281 “static” average atmospheric density, which is merely a function of elevation and does not consider
282 regional and seasonal atmospheric density variations. On the other hand, we cannot exclude that
283 the density may just be one of the factors influencing the bedforms dimensions. As suggested by
284 Lorenz (2020), wind speed at a global scale may increase with elevation creating a more complex
285 interplay between density, wind speed and resulting bedform size.

286

287 **5 Conclusions**

288 This survey provides improved measurements to evaluate the mechanisms that set the size
289 of bedform on Mars. We show that previous works used biased measurements, particularly for the
290 bedforms located in the Tharsis region. We investigated the uniqueness of the bedforms located in
291 this region, concluding that these bedforms form a distinct population and should be analyzed
292 separately from the more common dark-toned large ripples that cover dunes outside Tharsis.

293 Our survey covers a larger range of elevations than previous works, and for the first time
294 provides full wavelength mapping of extensive regions. Overall, our results are consistent with the
295 predictions of the “wind-drag” hypothesis, favoring the model that considers a saltation transport
296 saturation length. Still, the compiled morphometric data is not enough to refute the impact ripple
297 hypothesis, as that would probably require the integration of variable wind velocities for each site.

298 The compiled dataset corroborates the existence of a robust relation between the
299 wavelength of large dark-toned ripples and atmospheric density. Therefore, this new survey
300 complements and helps to validate the main concept introduced in Lapotre et al. (2016): that paleo-

301 atmospheric density can be inferred for Mars by looking at the aeolian sedimentary record,
302 providing an important tool to probe the evolution of the planet's environment.

303

304 **Acknowledgments**

305 This research was supported by CITEUC (UID/Multi/00611/2021&POCI-01- 0145-FEDER-
306 006922) and by FCT grant CEECIND/02981/2017. M. C. and S.S. were funded by NASA Mars
307 Data Analysis Program Grant 80NSSC20K1066. We thank the Laboratory for Advanced
308 Computing at University of Coimbra for providing computing resources.

309 We acknowledge the valuable comments and suggestions made by Mathieu Lapotre and two
310 anonymous reviewers to an earlier version of this work. We thank Rob Sullivan for insights on the
311 morphodynamics of impact ripples.

312

313

314 **Open Research**

315 HiRISE images used in this work are publicly available at the Planetary Data System
316 (<https://hirise-pds.lpl.arizona.edu/PDS/>) where details can be obtained at McEwen et al. (2007).
317 The morphometric database compiled in this study is available at
318 <https://doi.org/10.6084/m9.figshare.21064657>.

319

320

321 **References**

322 Andreotti, B, Claudin, P., & Pouliquen, O. (2006). Aeolian sand ripples: Experimental study of
323 fully developed states. *Physical Review Letters*, 96(2). <https://doi.org/Doi>
324 10.1103/Physrevlett.96.028001

325 Andreotti, Bruno, Claudin, P., Iversen, J. J., Merrison, J. P., & Rasmussen, K. R. (2021). A
326 lower-than-expected saltation threshold at Martian pressure and below. *Proceedings of the*
327 *National Academy of Sciences of the United States of America*, 118(5).
328 <https://doi.org/10.1073/pnas.2012386118>

329 Bagnold, R. A. (1954). *The Physics of Blown Sand and Desert Dunes* (2nd ed.). New York:
330 Dover Publications, INC.

- 331 Baker, M. M., Lapotre, M. G. A., Minitti, M. E., Newman, C. E., Sullivan, R., Weitz, C. M., et
332 al. (2018). The Bagnold Dunes in Southern Summer: Active Sediment Transport on Mars
333 Observed by the Curiosity Rover. *Geophysical Research Letters*, *45*(17), 8853–8863.
334 <https://doi.org/10.1029/2018GL079040>
- 335 Baker, M. M., Newman, C. E., Sullivan, R., Minitti, M. E., Edgett, K. S., Fey, D., et al. (2022).
336 Diurnal Variability in Aeolian Sediment Transport at Gale Crater, Mars. *Journal of*
337 *Geophysical Research: Planets*, *127*(2), 1–27. <https://doi.org/10.1029/2020JE006734>
- 338 Bridges, N. T., Banks, M. E., Beyer, R. A., Chuang, F. C., Noe Dobrea, E. Z., Herkenhoff, K. E.,
339 et al. (2010). Aeolian bedforms, yardangs, and indurated surfaces in the Tharsis Montes as
340 seen by the HiRISE Camera: Evidence for dust aggregates. *Icarus*, *205*(1), 165–182.
341 <https://doi.org/10.1016/j.icarus.2009.05.017>
- 342 Bridges, N. T., Ayoub, F., Avouac, J.-P., Leprince, S., Lucas, a, & Mattson, S. (2012). Earth-
343 like sand fluxes on Mars. *Nature*, *485*(7398), 339–42. <https://doi.org/10.1038/nature11022>
- 344 Cheng, H., Liu, C., Li, J., Liu, B., Zheng, Z., Zou, X., et al. (2018). Experimental study of
345 aeolian sand ripples in a wind tunnel. *Earth Surface Processes and Landforms*, *43*(1), 312–
346 321. <https://doi.org/10.1002/esp.4246>
- 347 Chojnacki, M., Vaz, D. A., Silvestro, S., & Silva, D. C. A. (2021). Widespread Megaripple
348 Activity Across the North Polar Ergs of Mars. *Journal of Geophysical Research: Planets*,
349 1–19. <https://doi.org/10.1029/2021je006970>
- 350 Day, M., & Zimbelman, J. R. (2021). Ripples, megaripples, and TARs, Oh, My!
351 Recommendations regarding Mars aeolian bedform terminology. *Icarus*, *369*, 114647.
352 <https://doi.org/10.1016/j.icarus.2021.114647>
- 353 Duran Vinent, O., Andreotti, B., Claudin, P., & Winter, C. (2019). A unified model of ripples
354 and dunes in water and planetary environments. *Nature Geoscience*, *12*(5), 345–350.
355 <https://doi.org/10.1038/s41561-019-0336-4>
- 356 Fenton, L. K. (2020). Updating the global inventory of dune fields on mars and identification of
357 many small dune fields. *Icarus*, *352*(May), 114018.
358 <https://doi.org/10.1016/j.icarus.2020.114018>
- 359 Foroutan, M., & Zimbelman, J. R. (2017). Semi-automatic mapping of linear-trending bedforms
360 using ‘Self-Organizing Maps’ algorithm. *Geomorphology*, *293*(May), 156–166.
361 <https://doi.org/10.1016/j.geomorph.2017.05.016>

- 362 Gonzalez, R. C., Woods, R. E., & Eddins, S. L. (2004). *Digital Image processing using*
363 *MATLAB*. Upper Saddle River, NJ: Pearson/Prentice Hall.
- 364 Gough, T. R., Hugenholtz, C. H., & Barchyn, T. E. (2021). Re-Evaluation of Large Martian
365 Ripples in Gale Crater: Granulometric Evidence for an Impact Mechanism and Terrestrial
366 Analogues. *Journal of Geophysical Research: Planets*, *126*(12).
367 <https://doi.org/10.1029/2021JE007011>
- 368 Hayward, R. K., Fenton, L. K., & Titus, T. N. (2014). Mars Global Digital Dune Database
369 (MGD3): Global dune distribution and wind pattern observations. *Icarus*, *230*, 38–46.
370 <https://doi.org/10.1016/j.icarus.2013.04.011>
- 371 Kok, J. F. (2010). An improved parameterization of wind-blown sand flux on Mars that includes
372 the effect of hysteresis. *Geophysical Research Letters*, *37*(12), 1–6.
373 <https://doi.org/10.1029/2010GL043646>
- 374 Lapotre, M. G. A., Ewing, R. C., Lamb, M. P., Fischer, W. W., Grotzinger, J. P., Rubin, D. M.,
375 et al. (2016). Large wind ripples on Mars: A record of atmospheric evolution. *Science*,
376 *353*(6294), 55–58. <https://doi.org/10.1126/science.aaf3206>
- 377 Lapotre, M. G. A., Ewing, R. C., Weitz, C. M., Lewis, K. W., Lamb, M. P., Ehlmann, B. L., &
378 Rubin, D. M. (2018). Morphologic Diversity of Martian Ripples: Implications for Large-
379 Ripple Formation. *Geophysical Research Letters*, *45*(19), 10,229–10,239.
380 <https://doi.org/10.1029/2018GL079029>
- 381 Lapotre, Mathieu G.A., Lamb, M. P., & McElroy, B. (2017). What sets the size of current
382 ripples? *Geology*, *45*(3), G38598.1. <https://doi.org/10.1130/G38598.1>
- 383 Lapotre, Mathieu G.A., Ewing, R. C., & Lamb, M. P. (2021). An Evolving Understanding of
384 Enigmatic Large Ripples on Mars. *Journal of Geophysical Research: Planets*, *126*(2), 1–8.
385 <https://doi.org/10.1029/2020JE006729>
- 386 Lorenz, R. D. (2020). Martian Ripples Making a Splash. *Journal of Geophysical Research:*
387 *Planets*, *125*(10), 12–15. <https://doi.org/10.1029/2020JE006658>
- 388 Lorenz, R. D., Bridges, N. T., Rosenthal, A. A., & Donkor, E. (2014). Elevation dependence of
389 bedform wavelength on Tharsis Montes, Mars: Atmospheric density as a controlling
390 parameter. *Icarus*, *230*, 77–80. <https://doi.org/10.1016/j.icarus.2013.10.026>
- 391 Manukyan, E., & Prigozhin, L. (2009). Formation of aeolian ripples and sand sorting. *Physical*
392 *Review E - Statistical, Nonlinear, and Soft Matter Physics*, *79*(3).

- 393 <https://doi.org/10.1103/PhysRevE.79.031303>
- 394 McEwen, A. S., Eliason, E. M., Bergstrom, J. W., Bridges, N. T., Hansen, C. J., Delamere, W.
395 A., et al. (2007). Mars Reconnaissance Orbiter's High Resolution Imaging Science
396 Experiment (HiRISE). *Journal of Geophysical Research-Planets*, 112(E5).
397 [https://doi.org/Doi 10.1029/2005je002605](https://doi.org/Doi%2010.1029/2005je002605)
- 398 Moller, M. F. (1993). A Scaled Conjugate-Gradient Algorithm for Fast Supervised Learning.
399 *Neural Networks*, 6(4), 525–533. [https://doi.org/Doi 10.1016/S0893-6080\(05\)80056-5](https://doi.org/Doi%2010.1016/S0893-6080(05)80056-5)
- 400 Putzig, N. E., & Mellon, M. T. (2007). Apparent thermal inertia and the surface heterogeneity of
401 Mars. *Icarus*, 191(1), 68–94. <https://doi.org/10.1016/j.icarus.2007.05.013>
- 402 Rasmussen, K. R., Valance, A., & Merrison, J. (2015). Laboratory studies of aeolian sediment
403 transport processes on planetary surfaces. *Geomorphology*, 244, 74–94.
404 <https://doi.org/10.1016/j.geomorph.2015.03.041>
- 405 Ruff, S. W., & Christensen, P. R. (2002). Bright and dark regions on Mars: Particle size and
406 mineralogical characteristics based on thermal emission spectrometer data. *Journal of*
407 *Geophysical Research E: Planets*, 107(12), 1–22. <https://doi.org/10.1029/2001je001580>
- 408 Sharp, R. P. (1963). Wind Ripples. *Journal of Geology*, 71(5), 617–636. Retrieved from
409 <http://www.jstor.org/stable/30061128>
- 410 Silvestro, S., Fenton, L. K., Vaz, D. A., Bridges, N. T., & Ori, G. G. (2010). Ripple migration
411 and dune activity on Mars: Evidence for dynamic wind processes. *Geophysical Research*
412 *Letters*, 37(20), L20203. [https://doi.org/Doi 10.1029/2010gl044743](https://doi.org/Doi%2010.1029/2010gl044743)
- 413 Silvestro, S., Vaz, D. A., Ewing, R. C., Rossi, A. P., Fenton, L. K., Michaels, T. I., et al. (2013).
414 Pervasive aeolian activity along rover Curiosity's traverse in Gale Crater, Mars. *Geology*,
415 41(4), 483–486. [https://doi.org/Doi 10.1130/G34162.1](https://doi.org/Doi%2010.1130/G34162.1)
- 416 Silvestro, S., Vaz, D. A., Yizhaq, H., & Esposito, F. (2016). Dune-like dynamic of Martian
417 Aeolian large ripples. *Geophysical Research Letters*, 43(16), 8384–8389.
418 <https://doi.org/10.1002/2016GL070014>
- 419 Silvestro, S., Chojnacki, M., Vaz, D. A., Cardinale, M., Yizhaq, H., & Esposito, F. (2020).
420 Megaripple Migration on Mars. *Journal of Geophysical Research: Planets*, 125(8).
421 <https://doi.org/10.1029/2020JE006446>
- 422 Smith, D. E., Zuber, M. T., Solomon, S. C., Phillips, R. J., Head, J. W., Garvin, J. B., et al.
423 (1999). The Global Topography of Mars and Implications for Surface Evolution, 284(May),

- 424 1495–1503.
- 425 Soille, P. (2002). *Morphological Image Analysis - Principles and Applications*. Berlin: Springer-
426 Verlag.
- 427 Sullivan, R., & Kok, J. F. (2017). Aeolian saltation on Mars at low wind speeds. *Journal of*
428 *Geophysical Research: Planets*, 122(10), 2111–2143.
429 <https://doi.org/10.1002/2017JE005275>
- 430 Sullivan, R., Kok, J. F., Kutra, I., & Yizhaq, H. (2020). A Broad Continuum of Aeolian Impact
431 Ripple Morphologies on Mars is Enabled by Low Wind Dynamic Pressures. *Journal of*
432 *Geophysical Research: Planets*, 125(10), 1–39. <https://doi.org/10.1029/2020je006485>
- 433 Sullivan, R., Baker, M., Newman, C., Turner, M., Schieber, J., Weitz, C., et al. (2022). The
434 Aeolian Environment in Glen Torridon, Gale Crater, Mars. *Journal of Geophysical*
435 *Research: Planets*, 127(8), 1–39. <https://doi.org/10.1029/2021JE007174>
- 436 Swann, C., Sherman, D. J., & Ewing, R. C. (2020). Experimentally Derived Thresholds for
437 Windblown Sand on Mars. *Geophysical Research Letters*, 47(3), 1–10.
438 <https://doi.org/10.1029/2019GL084484>
- 439 Taubman, D. S., & Marcellin, M. W. (2002). JPEG2000: Standard for interactive imaging.
440 *Proceedings of the IEEE*, 90(8), 1336–1357. <https://doi.org/10.1109/JPROC.2002.800725>
- 441 Vaz, D. A., & Silvestro, S. (2014). Mapping and characterization of small-scale aeolian
442 structures on Mars: An example from the MSL landing site in Gale Crater. *Icarus*, 230,
443 151–161.
- 444 Vaz, D. A., Sarmiento, P. T. K., Barata, M. T., Fenton, L. K., & Michaels, T. I. (2015). Object-
445 based Dune Analysis: Automated dune mapping and pattern characterization for Ganges
446 Chasma and Gale crater, Mars. *Geomorphology*, 250, 128–139.
447 <https://doi.org/10.1016/j.geomorph.2015.08.021>
- 448 Vaz, D. A., Silvestro, S., Sarmiento, P. T. K., & Cardinale, M. (2017). Migrating meter-scale
449 bedforms on Martian dark dunes: Are terrestrial aeolian ripples good analogues? *Aeolian*
450 *Research*, 26, 101–116. <https://doi.org/10.1016/j.aeolia.2016.08.003>
- 451 Voulgaris, G., & Morin, J. P. (2008). A long-term real time sea bed morphology evolution
452 system in the South Atlantic Bight. *Proceedings of the Ieee/Oes/Cmtc Ninth Working*
453 *Conference on Current Measurement Technology*, 71–79.
- 454 Weitz, C. M., Sullivan, R. J., Lapotre, M. G. A., Rowland, S. K., Grant, J. A., Baker, M., &

455 Yingst, R. A. (2018). Sand Grain Sizes and Shapes in Eolian Bedforms at Gale Crater,
456 Mars. *Geophysical Research Letters*, 45(18), 9471–9479.

457 <https://doi.org/10.1029/2018GL078972>

458 Withers, P., & Smith, M. D. (2006). Atmospheric entry profiles from the Mars Exploration
459 Rovers Spirit and Opportunity. *Icarus*, 185(1), 133–142.

460 <https://doi.org/10.1016/j.icarus.2006.06.013>

461