

# *Widespread Megaripple Activity Across the North Polar Ergs of Mars*

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## **Key Points:**

- Abundant megaripple populations were identified across the north polar ergs of Mars and found to be migrating with dunes and ripples.
- Polar megaripple dynamics and sand fluxes are enhanced relative to lower-latitude sites, despite the shorter migration season due to ice.
- Seasonal sublimation winds and polar storms were attributed as the cause for the elevated activity rather than cryospheric processes.

1 **Descriptive headings for each section:**

2 1. Introduction and motivation – introduction and motivation for the study, including a broad  
3 overview of aeolian bedforms.

4

5 2. Study region – a brief description of the north polar region and details regarding its past and  
6 current geology.

7

8 3. Overview of data sets and methods – details for our methodology and stated objectives.

9

10 4. Results – a description of results related for objectives 1-3: survey of polar megaripple  
11 occurrence, assessment of polar megaripple activity, and polar megaripple fluxes and comparisons  
12 to other bedforms.

13

14 5. Discussion – an examination on the spatial heterogeneity of polar intermediate-scale bedforms  
15 and the implications of the polar seasonal cycle on aeolian sand fluxes.

16

17 6. Conclusions: a summary of results and their possible implications.

18 **ABSTRACT**

19 The most expansive dune fields on Mars surround the northern polar cap where various aeolian  
20 bedform classes are modified by wind and ice. The morphology and dynamics of these ripples,  
21 intermediate-scale bedforms (termed megaripples and transverse aeolian ridges (TARs)), and sand  
22 dunes reflect information regarding regional boundary conditions. We found that populations of  
23 polar megaripples and larger TARs are distinct in terms of their morphology, spatial distribution,  
24 and mobility. Whereas regionally-restricted TARs appeared degraded and static in long-baseline  
25 observations, polar megaripples were not only widespread but migrating at relatively high rates  
26 ( $0.13 \pm 0.03$  m/yr) and possibly more active than other regions on Mars. This high level of activity  
27 is somewhat surprising since there is limited seasonality for aeolian transport due to surficial frost  
28 and ice during the latter half of the martian year. A comprehensive analysis of an Olympia Cavi  
29 dune field estimated that the advancement of megaripples, ripples, and dunes avalanches  
30 accounted for  $\sim 1\%$ ,  $\sim 10\%$ , and  $\sim 100\%$ , respectively, of the total aeolian system's sand fluxes. This  
31 included dark-toned ripples that migrated the average equivalent of  $9.6 \pm 6$  m/yr over just 22 days  
32 in northern summer – unprecedented rates for Mars. While bedform transport rates are some of  
33 the highest yet reported on Mars, the sand flux contribution between the different bedforms does  
34 not substantially vary from equatorial sites with lower rates. Seasonal off-cap sublimation winds  
35 and summer-time polar storms are attributed as the cause for the elevated activity, rather than  
36 cryospheric processes.

37

38 **Plain Language Summary**

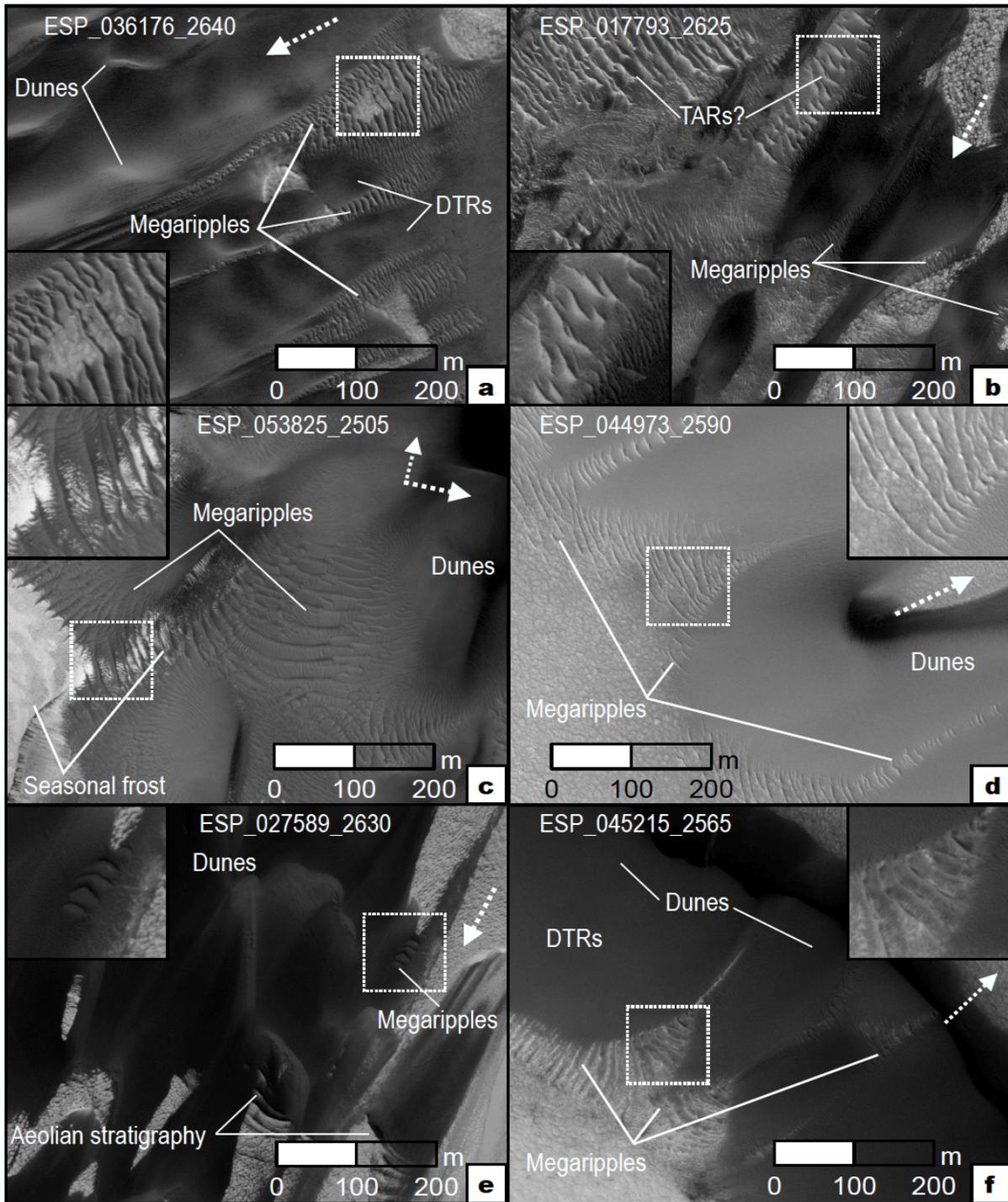
39 “Megaripples” are distinct wind-driven bedforms that occur on the surface of Earth and Mars,  
40 often with sizes between that of smaller ripples and larger dunes. Recent work has found the thin  
41 martian atmosphere is capable of mobilizing some coarse-grained megaripples, overturning prior  
42 notions that these were static relic landforms from a past climate. We mapped megaripples and  
43 adjacent bedforms across the north polar sand seas, the most expansive collection of dune fields  
44 on Mars. Megaripples were found to be widespread across the region and migrating at relatively  
45 high rates relative to other sites on Mars that are at lower latitudes. This enhanced activity is likely  
46 related to the greater sand fluxes found for neighboring dunes which are driven by summer-time  
47 seasonal winds when polar ice is sublimating.

## 48 1.0 Introduction and motivation

49 Dune fields across Earth and Mars host a variety of aeolian bedform classes (e.g., ripples,  
50 megaripples, dunes) that vary in terms of size and particle size distribution (Bagnold, 1941;  
51 Wilson, 1973; Greeley and Iversen, 1985). Planetary bedform types include sand dunes, decimeter-  
52 wavelength impact ripples, and the generally larger ripple class of coarse-grained “megaripples”  
53 (Greeley et al., 1992; Malin and Edgett, 2001; Sullivan et al., 2005, 2008; Lancaster, 2009).  
54 Martian dark-toned, decameter-wavelength ripples are an exception, with no counterpart in  
55 terrestrial eolian environments (Vaz et al., 2017). The last several decades of Mars exploration and  
56 the arrival of high resolution orbital imaging and surface rovers have also revealed some of these  
57 bedform classes are migrating under the current climate (Sullivan et al., 2005; Silvestro et al.,  
58 2010, 2020; Chojnacki et al., 2015). Ultimately the presence and activity of a given bedform class  
59 reflects differences in their boundary conditions (e.g., grain size, wind energy, sediment supply)  
60 (Kocurek and Ewing, 2012; Chojnacki et al., 2019). For example, terrestrial megaripples that are  
61 often partially sourced by an abundant coarse sand population may rarely migrate except for very  
62 strong storm events (Sakamoto-Arnold, 1981a; Isenberg et al., 2011a).

63 The smallest bedform class observed from orbit on Mars (1-5 m spacing and ~40 cm tall)  
64 are dark-toned ripples (DTRs) found migrating atop dunes or within isolated patches (Bridges et  
65 al., 2011; Lapotre et al., 2016, 2018; Sullivan and Kok, 2017). The larger (10-100 m spacing and  
66 1-14 m tall), light-toned Transverse Aeolian Ridges (TARs) can occur in association with dunes  
67 or as large TAR fields, but often lack unambiguous signs of activity (Balme et al., 2008; Geissler  
68 and Wilgus, 2017; Berman et al., 2018). The size range in between these commonly cited bedform  
69 populations (5-40 m spacing, ~1-2 m tall) have been largely unexplored and generally assumed to  
70 be inactive like TARs (Chojnacki et al., 2018). We term these intermediate-scale bedforms as  
71 “megaripples” based on their greater dimensions and brighter crests than DTRs (**Fig. 1**), where we  
72 infer the latter is due to a coarser grain size component (Greeley and Iversen, 1985). It is noted  
73 that granulometrical analysis, which is required to properly distinguish between unimodal and  
74 bimodal sand of a given bedform (Greeley and Iversen, 1985; Sullivan et al., 2008; Yizhaq et al.,  
75 2012), is unavailable for most locations on Mars.

76 Recent analysis using images acquired by the High Resolution Imaging Science  
77 Experiment (HiRISE) camera (0.25–1 m/pix) (McEwen et al., 2007) have shown certain locations



**Fig. 1.** (a-f) Polar bedform sites with active megaripples, as viewed in HiRISE at the same scale. Approximate transport directions (dashed arrows) are shown. Insets are 100-m-wide. All images are oriented North up unless otherwise indicated. (a) High flux bedforms in the Olympia Cavi dune field termed "Buzzel". (b) Polar bedforms that resemble TARs, alongside DTRs and megaripples. (c) Loath crater megaripples, some partially restricted by late season frost and possible intergranular ice. (d) Bright, thin megaripples found to be active in Scandi Cavi. (e) Modern bedforms that migrate over aeolian stratigraphy described by Brothers and Kocurek (2018). (f) Megaripples arranged upwind and flanking inter-erg mega-dunes.

79 2019; Silvestro et al., 2020). However, it is not clear how frequent this mobility is or even their  
80 broader occurrence. In particular, the northern polar latitudes of Mars has been found to have  
81 extensive migration of DTRs and dunes (Hansen et al., 2011; Bridges et al., 2011; Chojnacki et  
82 al., 2019; Fenton et al., 2021), but also has been cited to lack intermediate-scale bedforms of  
83 megaripples or TARs (Wilson and Zimbelman, 2004; Balme et al., 2008). Additionally, this effort  
84 seeks to constrain the sand flux contributions of megaripples relative to other polar bedforms.

85         The goal of this project is to better understand the intriguing bedform class of megaripples  
86 in one of the most complex planetary aeolian systems, namely the north circumpolar ergs.  
87 Objectives here are to 1) survey aeolian sites across the north pole of Mars for the presence of  
88 intermediate-scale bedforms, 2) assess megaripple and TAR dynamics and evaluate if any activity  
89 is restricted to certain areas or is widespread across polar sites, and 3) quantify relative sand flux  
90 contributions of polar megaripples related to other bedforms. All of the objective results will be  
91 viewed in the context of the polar environment and how regional boundary conditions impact  
92 bedform mobility across the erg. In this way, we hope to better understand polar aeolian processes,  
93 identify any seasonal effects, and quantify landscape evolution in one of the most active regions  
94 on Mars.

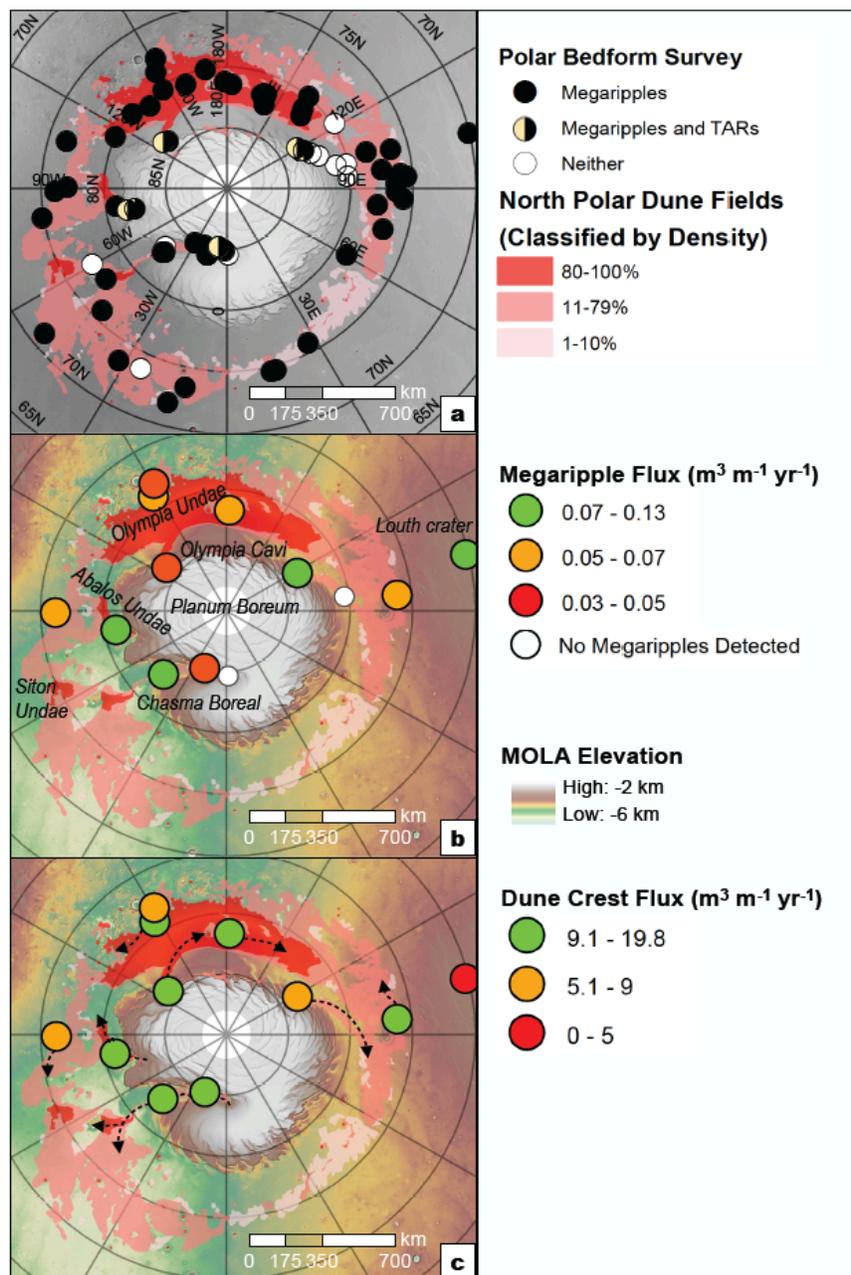
## 95         **2.0 Study Region**

96         The north polar region of Mars displays a range of seasonal and annual atmospheric and  
97 surface processes that continually reshape the local landscape (Smith et al., 2018). These processes  
98 are linked to the volatile and dust exchange between polar and nonpolar reservoirs, where the north  
99 polar cap is composed of seasonal CO<sub>2</sub> ice, residual H<sub>2</sub>O ice, and dust (Langevin, 2005; Khayat et  
100 al., 2019). This surface-atmospheric exchange is known to drive various aeolian phenomena, such  
101 as wind streaks (Howard, 2000), seasonal and inter-annual albedo variations (Calvin et al., 2015),  
102 spiral trough evolution (Smith and Holt, 2010), dust storms (Wang and Fisher, 2009) and bedform  
103 migration (Bourke et al., 2008; Bridges et al., 2011). Expansive dune systems nearest the north  
104 polar layered deposits (NPLD) and residual cap (Hayward, 2011; Fenton, 2020) are primarily  
105 driven by Coriolis force deflected katabatic (downslope) winds from the northeast descending into  
106 a series of reentrant chasms. Indeed, sand pathways sourced from the NPLD's Planum Boreum  
107 cavi and Rupes units are most evident in Chasma Boreale, Olympia Cavi, and other reentrants that  
108 spiral southward to merge with the main erg (**Fig. 2**)(Fishbaugh and Head, 2005; Tanaka et al.,  
109 2008). The high level of bedform migration is despite the limited sediment availability caused by

110 autumn/winter CO<sub>2</sub>/H<sub>2</sub>O ice accumulation that restricts saltation for most of the year (Chojnacki  
 111 et al., 2019). Dune sand  
 112 becomes ice-cemented while  
 113 winter-time CO<sub>2</sub> ice buries  
 114 dunes and then slowly  
 115 sublimates through the  
 116 Northern spring/summer  
 117 until bedforms are “frost  
 118 free” and mobile by summer  
 119 (Ewing et al., 2010; Hansen  
 120 et al., 2011). Some ice-  
 121 cemented bedforms do not  
 122 appear to regain mobility  
 123 and were deposited into the  
 124 geologic record as evidenced  
 125 by the exposed aeolian  
 126 cross-strata (Brothers and  
 127 Kocurek, 2018).

### 128 3.0 Overview of 129 Approach Data Sets 130 and Methods

131 For the objective 1  
 132 survey we assessed bedform  
 133 morphology using HiRISE  
 134 images (0.25–1 m/pix)  
 135 acquired in northern summer  
 136 and criteria described in  
 137 section 4.1. Objective 2 and  
 138 3’s assessment of bedform  
 139 activity relied on long-  
 140 baseline (4-7 Mars years)



**Figure 2.** Polar bedform occurrence and activity results. Dune field distribution are shown in red (Hayward et al., 2014; Fenton, 2020). Base maps are MOLA shaded relief with gray-scale or colored elevation. (a) Survey results showing HiRISE locations of dune fields with megaripples, TAR-candidates, or sites lacking either intermediate-scale bedform class. See Table S2. (b) Results showing megaripple fluxes (colored circles) from manual mapping along with two sites lacking megaripples (white circles; Fig. S1). (c) Prior results showing sand dune fluxes at the same locations (colored circles; Chojnacki et al. 2019) and simplified transport directions (dashed arrows).

141 orthoimages of sites with prior HiRISE Digital Terrain Models (DTMs) (1 m/post) (Chojnacki et  
142 al., 2019). Orthorectification was carried out using SOCET SET® BAE system photogrammetry  
143 software (Kirk et al., 2008), where image pairs for change detection were typically acquired within  
144 20° of solar longitude ( $L_s$ ), but in different Mars years (see Supplementary Materials (SM) section  
145 1 for more details). Activity was quantified by mapping 3 or more consecutive megaripple crests  
146 (per area) in both the Time 1 (T1) and T2 images (**Table S1**) using ArcGIS® or QGIS. Wavelength  
147 ( $w_r$ ) and migration rate (m/Earth-year) were calculated using QGIS software and in-house code  
148 which ingests manually mapped crest lines from different images. Wavelength measurements  
149 correspond to the average spacing computed along transects orthogonal to the bedform traces,  
150 while migration rates were quantified assuming a local bi-orthogonal migration trend between  
151 mapped crest lines (Silvestro et al., 2020). Bedform half heights ( $h_r$ ), and ultimately megaripple  
152 flux estimates, were derived using the following relationship (Bridges et al., 2012);

$$153 \quad (1) \quad h_r = w_r / 20$$

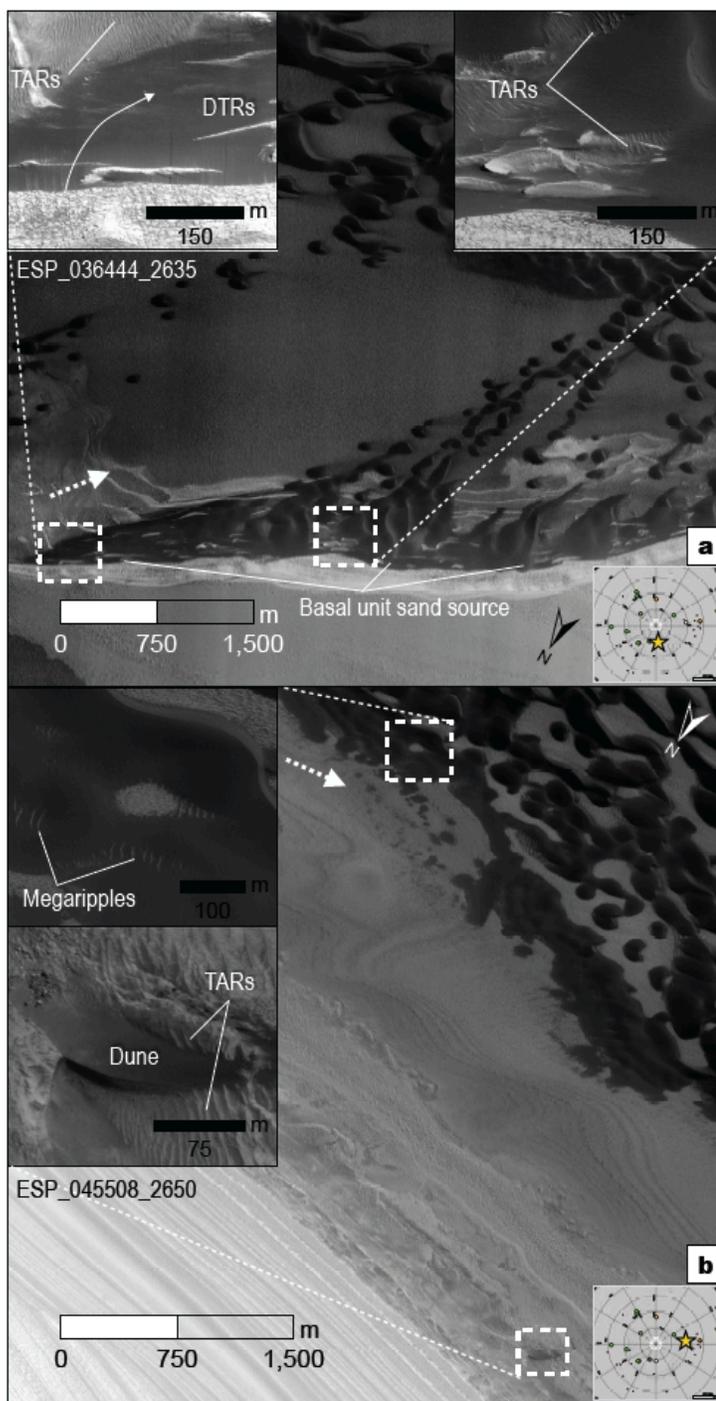
154 Objective 3's quantification of whole dune field fluxes required multiple approaches  
155 applied to an Olympia Cavi reentrant aeolian site (232.9°E; 84.0°N) termed here as "Buzzel" (see  
156 Diniega et al. (2017)). This site was chosen due to the abundance of adequate data and known  
157 activity (Diniega et al., 2017; Chojnacki et al., 2019). Dune front advancements were recorded  
158 with the tracing of lee fronts in ArcMap® on the T1 and T2 images, allowing migration rates and  
159 directions to be semiautomatically computed. This process integrates data derived from HiRISE  
160 orthoimages and DTMs, generating continuous measurements of migration and heights along the  
161 slip faces (Urso et al., 2018). Migration vectors were then converted to volumetric sand fluxes ( $q$ )  
162 ( $m^3 m^{-1} yr^{-1}$ ) by multiplying the migration rates to the dune slip face heights. Instead of reporting  
163 peak fluxes (multiplying the maximum height by the average migration, like in Urso et al. (2018))  
164 we compute mean and median fluxes by multiplying the two variable parameters along the slip  
165 faces. This generates lower average fluxes, yet it is a more accurate representation of the overall  
166 fluxes (the same approach was followed in the flux comparison presented by Silvestro et al., 2020).  
167 Ripple and megaripple displacements were quantified for the Buzzel site using "Co-registration of  
168 Optically Sensed Images and Correlation" (COSI-Corr) software (Leprince et al., 2007) which  
169 produces a dense vectorial map of ripple migration (Bridges et al., 2012; Vaz et al., 2017). The

170 rapid migration rates of DTRs  
 171 required early summer images (Mars  
 172 Year (MY) 35,  $L_s$  95-105°), whereas  
 173 MY 30 and 35 images were used to  
 174 assess slower megaripples. Fluxes  
 175 were derived using the method of  
 176 Silvestro et al. (2020). For flux  
 177 comparison purposes, all three  
 178 bedform classes were characterized in  
 179 the northeast ~1-2 km (upwind)  
 180 section of the dune field based on  
 181 image pair constraints (See SM  
 182 section 2 for more details).

#### 183 4.0 Results

##### 184 4.1 Survey of polar megaripple 185 occurrence

186 We surveyed dune fields  
 187 imaged by HiRISE across all latitudes  
 188 above 65°N to assess the presence or  
 189 absence of intermediate-scaled  
 190 bedforms (**Fig. 1, 2a**). TARs and  
 191 megaripples were classified separately  
 192 based on their different size, albedo,  
 193 and stratigraphic relationship (**Fig. 1**).  
 194 TAR candidates were designated for  
 195 light-toned, transverse bedforms,  
 196 which were interpreted as being  
 197 stratigraphically below dark dunes and  
 198 meter-scale ripples (**Fig. 1b**). In  
 199 contrast, megaripples were noted to be  
 200 present for typically smaller, variable-

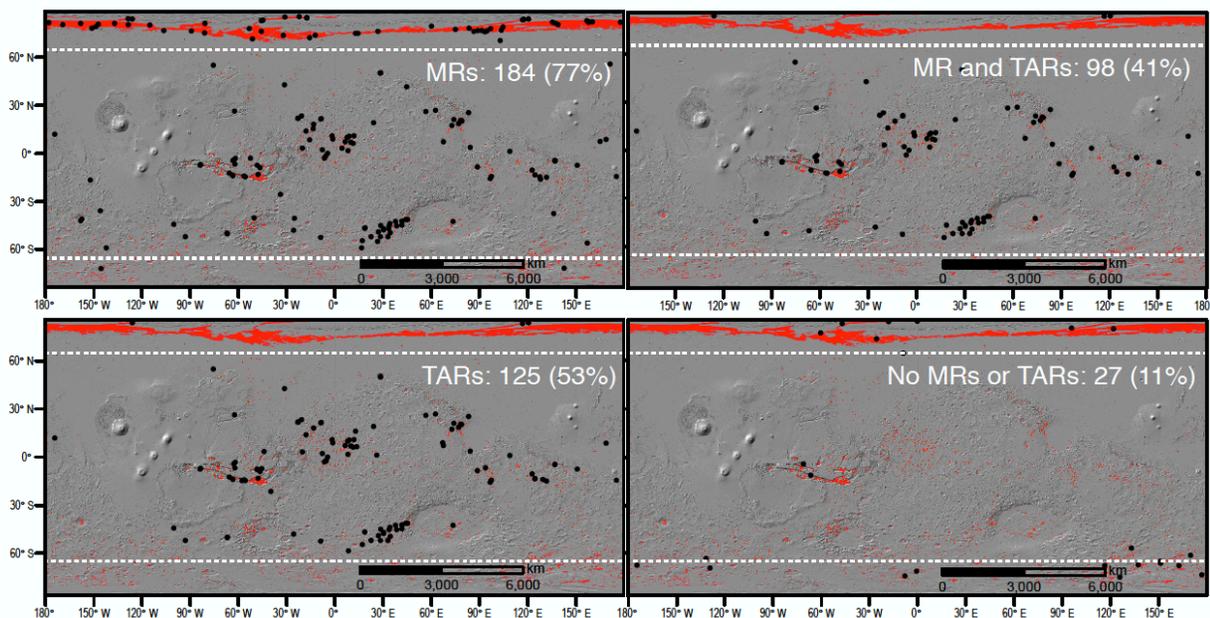


**Figure 3.** Examples of polar megaripples and TARs near the NPLD and basal unit sand sources at (a) Chasma Boreale and (b) west Olympia Cavi. Along with being underneath some dark dunes or ripples, polar TARs can be found superposed with boulders or with crests in opposing directions as nearby dunes transport. Approximate transport directions (dashed arrows) are shown. Inset maps show site locations (star).

201 albedo bedforms which were in most cases stratigraphically above or in continuity with  
 202 neighboring bedforms (**Fig. 1a**). Of the 67 locations surveyed, 88.1% had megaripples, 9.0% had  
 203 TARs, 9.0% had both, and 11.9% had neither class of intermediate-sized bedforms (**Table S2**).  
 204 DTRs were found at all erg locations. Megaripples were commonly found upwind of erg areas,  
 205 climbing dune slopes, or in small inter-dune fields. Bright-toned TARs were identified in large  
 206 fields below scarps or under swifter dark bedforms, but dominantly nearest the NPLD-erg margins  
 207 (**Fig. 2a, 3, 4**). Likewise, the greatest proportion of HiRISE images lacking either intermediate-  
 208 sized class were in these higher latitude areas (**Fig. 2a, S1**). Prior global surveys had described in  
 209 passing the lack of TARs in polar regions compared with lower-latitude regions (Wilson and  
 210 Zimbelman, 2004; Balme et al., 2008). More recently, Chojnacki et al. (2021) did a global HiRISE  
 211 survey and identified close to half of all sites (52.5%) had bedforms identified as TARs (**Fig. 4**;  
 212 **Table S2**).

#### 213 4.2 Assessment of polar megaripple activity

214 To qualitatively and quantitatively assess the activity of polar megaripples we examined  
 215 HiRISE long-baseline orthoimages (**Table S1**). Of the 13 monitoring sites in the north polar ergs,  
 216 85% (11) showed unambiguous migration of megaripples in (downwind) directions that are  
 217 broadly aligned with that of nearby DTRs and dunes (**Fig. 2b**; **Animation S1-S5**). The remaining



**Figure 4.** Global trends of intermediate-sized aeolian bedforms (black circles) using HiRISE images of dune fields. Megaripples (MR) and Transverse Aeolian Ridges (TARs) were classified separately based on their different size, albedo, and stratigraphic relationship. Compare with earlier MOC-based results (Wilson & Zimbelman, 2004). Base maps are MOLA shaded relief with dunes field in red (Hayward et al., 2014; Fenton, 2020).

**Table 1.** Polar megaripple activity results (Objective 2). Reported values are median  $\pm$  median absolute deviations. The first two sites of McLaughlin crater and Nili Fossae are the lower latitude fields discussed by Silvestro, et al. (2020). Also see Fig. 2, 5.

<u>Site ID and Name<sup>a</sup></u>	<u>Elapsed time (EY)<sup>b</sup></u>	<u>Displacement (m)</u>	<u>Migration rate (m/yr)</u>	<u>Wavelength (m)</u>	<u>Half average height (m)</u>	<u>Flux (m<sup>3</sup> m<sup>-1</sup>yr<sup>-1</sup>)</u>	<u>N</u>
3374+216 McLaughlin	7.57	0.97 $\pm$ 0.5	0.13 $\pm$ 0.06	6.7 $\pm$ 1	0.34 $\pm$ 0.05	0.042 $\pm$ 0.02	3215
0742+214 NiliFossae	9.38	1.4 $\pm$ 0.8	0.15 $\pm$ 0.09	7.1 $\pm$ 1	0.35 $\pm$ 0.05	0.051 $\pm$ 0.03	1828
2329+840 BuzzelDunes <sup>c</sup>	9.50	0.96 $\pm$ 0.4	0.1 $\pm$ 0.05	6.9 $\pm$ 0.9	0.34 $\pm$ 0.05	0.034 $\pm$ 0.02	2671
0953+761 PalmaDunes	9.33	1.4 $\pm$ 0.5	0.15 $\pm$ 0.06	7.8 $\pm$ 1	0.39 $\pm$ 0.05	0.056 $\pm$ 0.03	443
2121+790 GypsumErg	7.59	1 $\pm$ 0.2	0.13 $\pm$ 0.03	7.8 $\pm$ 0.6	0.39 $\pm$ 0.03	0.053 $\pm$ 0.01	302
1788+816 OlympiaUndae	7.47	1.1 $\pm$ 0.3	0.15 $\pm$ 0.04	8.7 $\pm$ 0.4	0.44 $\pm$ 0.02	0.064 $\pm$ 0.02	195
1035+703 LouthCrater	12.92	2.4 $\pm$ 0.4	0.19 $\pm$ 0.03	8.3 $\pm$ 1	0.42 $\pm$ 0.06	0.071 $\pm$ 0.02	200
1186+835 TleilaxDunes	11.00	1.8 $\pm$ 0.3	0.16 $\pm$ 0.03	8.8 $\pm$ 0.9	0.44 $\pm$ 0.05	0.069 $\pm$ 0.01	260
2798+809 AbalosScopuli	9.47	2.5 $\pm$ 0.6	0.26 $\pm$ 0.06	7.6 $\pm$ 1	0.38 $\pm$ 0.05	0.099 $\pm$ 0.03	375
2705+761 AbalosDunes	11.30	1.8 $\pm$ 0.3	0.16 $\pm$ 0.03	7.1 $\pm$ 1	0.36 $\pm$ 0.05	0.058 $\pm$ 0.01	370
3393+850 ChasmaBoreale	11.23	1.1 $\pm$ 0.4	0.095 $\pm$ 0.03	7.3 $\pm$ 1	0.36 $\pm$ 0.06	0.034 $\pm$ 0.01	521
2095+780 ScandiaCavi	11.27	1.2 $\pm$ 0.3	0.1 $\pm$ 0.02	9 $\pm$ 0.5	0.45 $\pm$ 0.02	0.045 $\pm$ 0.009	254
3154+827 ChasmaBoreale- MegadunesI	7.63	1.8 $\pm$ 0.6	0.24 $\pm$ 0.08	6.8 $\pm$ 0.9	0.34 $\pm$ 0.04	0.083 $\pm$ 0.03	145
All areas		1.2 $\pm$ 0.6	0.13 $\pm$ 0.06	7.1 $\pm$ 1	0.36 $\pm$ 0.06	0.046 $\pm$ 0.02	10779

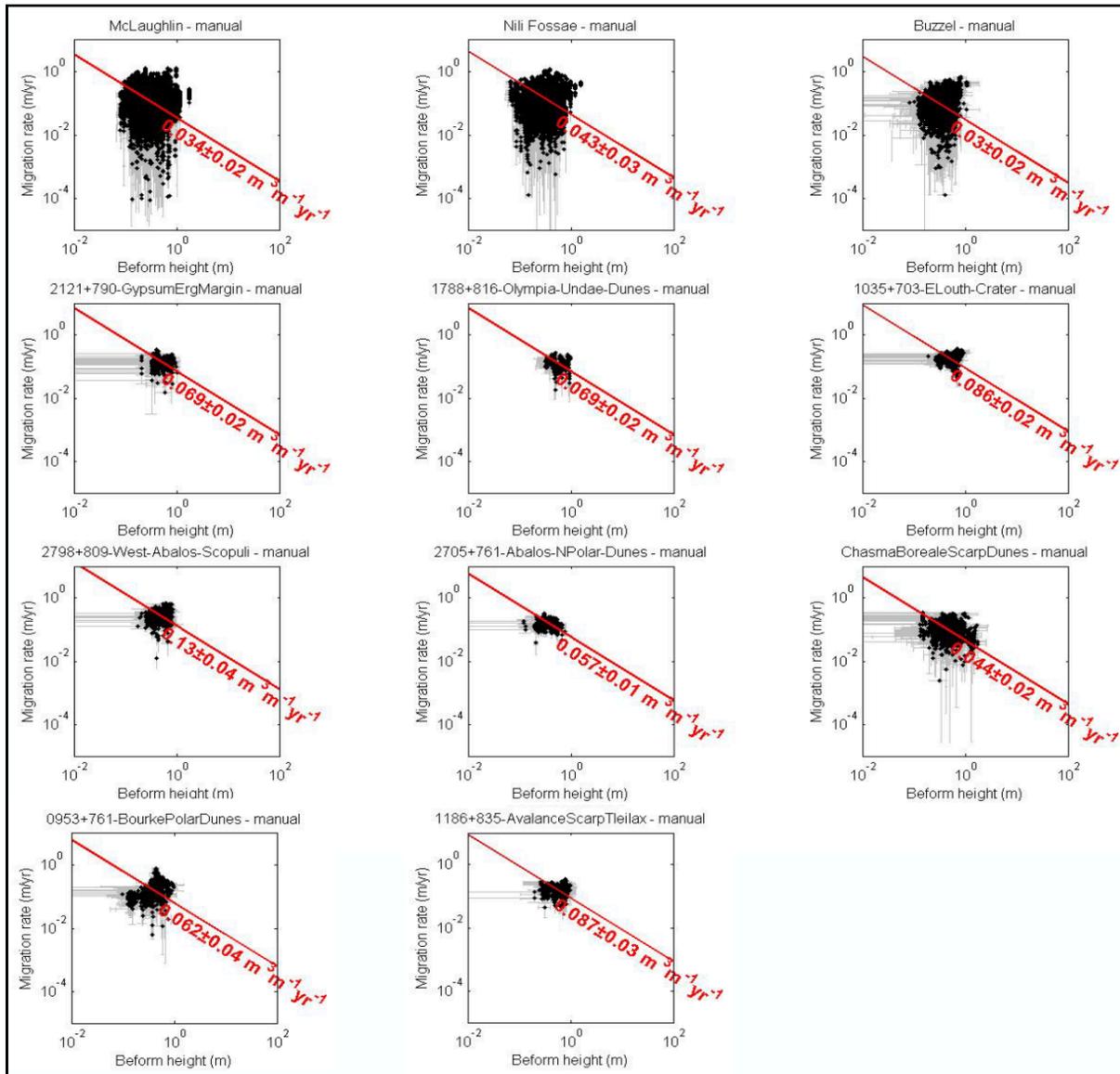
<sup>a</sup>Dune field site IDs, where the first four digits are the monitoring site's centroid east longitude, the last three digits are the site's latitude (no decimals), and the "+" indicates the northern hemisphere. Informal site names are also provided where some correspond with those investigated by Diniega et al. (2017).

<sup>b</sup>See Table S1 for relevant HiRISE data information.

<sup>c</sup>The values for the Buzzel dunes correspond to the mapping of the full area (a total of 247 slip faces), while the measurements discussed in section 4.3 correspond to a buffer area (148 slip faces) shown in Fig. 6-7.

218 two sites had no megaripples present to observe, although DTRs and dunes were migrating at those  
219 locations (**Fig. S1**). Megaripple activity is most evident on the upwind edges of dune fields and in

220 some cases within inter-erg areas or below arcuate scarps. Clusters of contiguous megaripple fields  
 221 often flanked by ripples and dunes were most common, while occasionally occurrences of mobile  
 222 megaripple trains atop of bedrock were observed (Fig. 1a, Animation S3). Crestlines may  
 223 bifurcate, split, or merge with other megaripples moving at slower rates resulting in changes in  
 224 crest-line patterns. In many cases, unambiguous megaripple migration was observed in shorter-  
 225 term annual pairs as well (2-3 Mars years). Some of these swifter examples migrating several  
 226 wavelengths made them difficult to track in longer baseline image pairs, whereas certain slower



**Figure 5.** Megaripple sand flux results for 11 polar sites as compared with those in McLaughlin/Nili Fossae (top left two plots, Silvestro et al. 2020). Migration rates (y-axis) were derived from crestline mapping whereas heights (x-axis) were computed from wavelength-height relationships. Median sand fluxes ( $\pm$  median absolute deviation) are reported in red. Corresponding wavelength are provided in Fig. S2.

227 ones were overtaken and buried by dunes (**Animation S6-S7**). In contrast, all occurrences of polar  
228 TARs remained static at the time-scale and spatial resolution of this survey.

229 The median wavelength for active megaripple sites ranged between 5.8-11 m (average  
230  $7.2 \pm 2$  m (**Fig. S2**); all reported uncertainties correspond to  $1\sigma$ ) and rates between 0.08-0.27 m/yr  
231 ( $0.13 \pm 0.06$  m/yr for all sites)(**Fig. 5; Table 1; S2**). For comparison global average dune rates were  
232  $\sim 0.5$  m/yr (Chojnacki et al., 2019), average southern latitude ripple rates were 0.35 m/yr (Banks et  
233 al., 2018), and tropical latitude megaripples migrated at 0.12–0.13 m/yr (Silvestro et al., 2020).  
234 Average wavelength-derived heights for all sites were between 0.7-0.9 m (**Table 1**), but  
235 topographic profiles show some individual megaripples 1-2-m-tall (**Fig. S3**). The manually derived  
236 median megaripple sand fluxes ranged between 0.034-0.099  $\text{m}^3\text{m}^{-1}\text{yr}^{-1}$  (average  $q = 0.046 \pm 0.02$   
237  $\text{m}^3\text{m}^{-1}\text{yr}^{-1}$ ) (**Fig. 2b, 5; Table 1**). Average sand dune crest fluxes for all but one of these sites (Louth  
238 crater) were moderate to high ( $7.4$ - $18.6$   $\text{m}^3\text{m}^{-1}\text{yr}^{-1}$ ) based on earlier measurements (**Fig. 2c**;  
239 (Chojnacki et al., 2019)). A comparison between the megaripple and sand dune flux distributions  
240 (**Fig. 2b-c**) shows a moderate correlation for monitoring sites implying a relation. That is, moderate  
241 to high flux dune fields tend to host a similar or lower megaripple flux classification, albeit  
242 threshold levels between flux classes are somewhat arbitrary. However, a more holistic approach  
243 is required to better understand the spatial and temporal aspects of megaripples within a given  
244 aeolian system (see **4.3**). Overall, we found that polar megaripple activity is widespread in various  
245 contexts (e.g., reentrant troughs, inter-ergs, polar craters), whereas static TAR candidates  
246 displayed rounded, broad, or pitted crests were found within otherwise active sand corridors  
247 adjacent to the NPLD (**Fig. 2b-2c, Animation S8**; see Section 5.2).

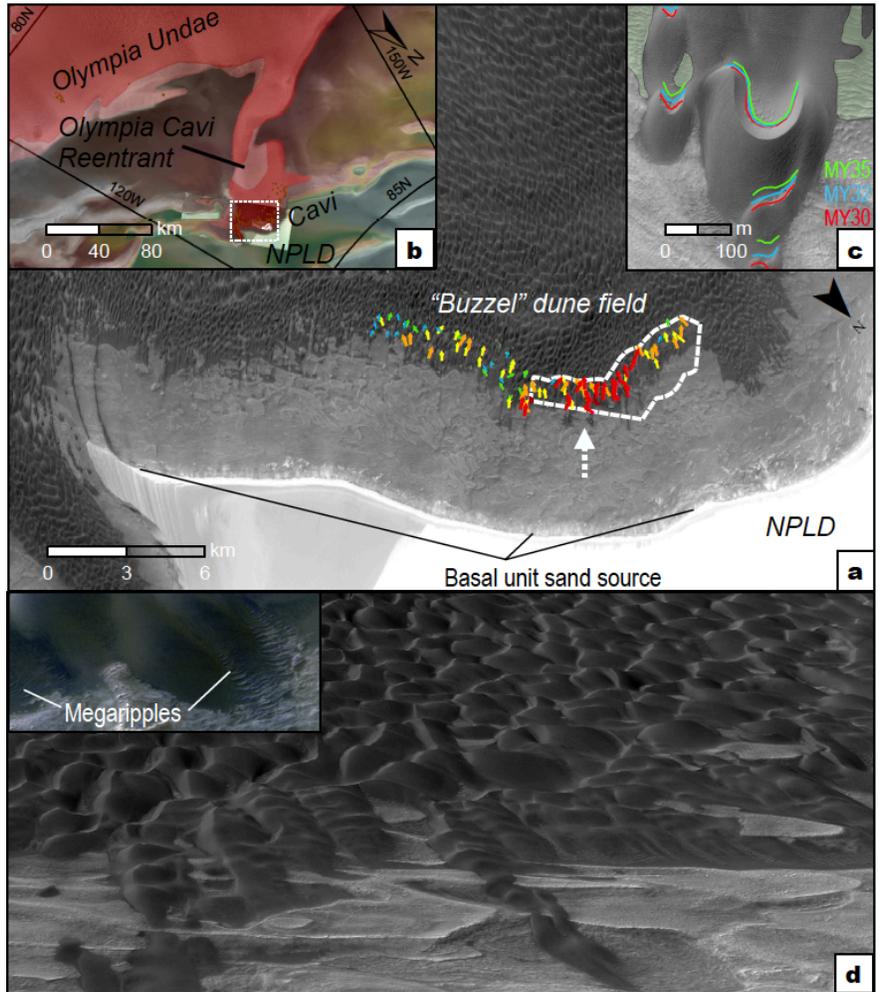
### 248 **4.3 Polar megaripple fluxes and comparisons to other bedforms**

249 The Buzzel site represents a typical polar trough dune field, which is located just downwind  
250 of its basal unit sand source (**Fig. 6**) (Fishbaugh and Head, 2005; Nerozzi and Holt, 2019). Proto  
251 dunes and sand sheets lead southwestward to more developed barchans and barchanoids as  
252 sediment supply increases (Ewing et al., 2015). In order to best constrain whole dune field fluxes  
253 we used a buffer area located on the upwind edge of the site (**Fig. 6a**), this way we obtained  
254 collocated flux measurements of all bedform classes. Sand dune migration rates (0.2-5.4 m/yr) and  
255 fluxes ( $1.1$ - $35.7$   $\text{m}^3\text{m}^{-1}\text{yr}^{-1}$ ) broadly decrease downwind to the southwest, but are quite variable in  
256 the cross-field directions (NW-SE)(**Fig. 7a, S4; Table 2**). Dune measurements were collected for

257 two consecutive time periods (spanning 3.8 and 5.7 EY), resulting in similar fluxes, respectively  
 258  $10.5 \pm 8$  and  $7.3 \pm 6$   $\text{m}^3\text{m}^{-1}\text{yr}^{-1}$  average fluxes (**Fig. 6c, S4, Animation S9**).

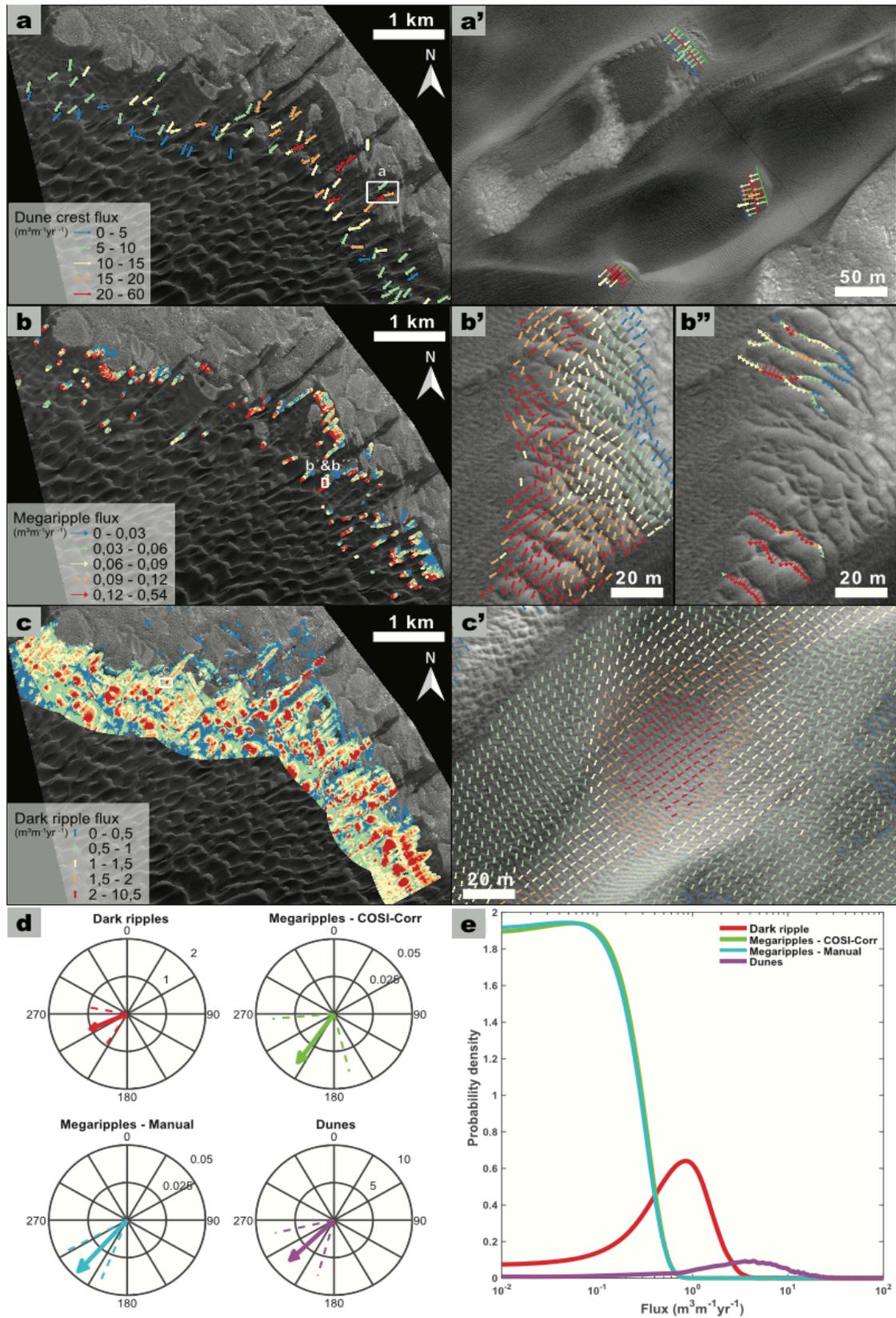
259 Dark-toned ripples migrated at high rates throughout the site but are greatest along higher  
 260 dune slopes and crests (**Fig. 7c**). Indeed, DTR migration rates ranged from 1-84 m/yr and averaged  
 261 a high value of  $9.6 \pm 6$  m/yr in the brief period between images ( $L_s$  94.96-105.08° or 22.6 days in  
 262 MY35/2019). A longer  
 263 baseline pair ( $L_s$  105.08-  
 264 128.4°) was investigated,  
 265 but ripples had displaced  
 266 too much for the COSI-Corr  
 267 correlator to track them  
 268 preventing a more precise  
 269 computation of the  
 270 migration rates. Associated  
 271 DTRs fluxes were  $0.2$ - $10$   
 272  $\text{m}^3\text{m}^{-1}\text{yr}^{-1}$  (average  $q = 1.2 \pm$   
 273  $0.8$   $\text{m}^3\text{m}^{-1}\text{yr}^{-1}$ ) (**Fig. 7e**).

274 Megaripples are  
 275 distributed across the study  
 276 area but more often in the  
 277 upwind locations (**Fig. 7b**).  
 278 Megaripple sand fluxes  
 279 here were  $0.05$ - $0.5$   $\text{m}^3\text{m}^{-1}\text{yr}^{-1}$   
 280 <sup>1</sup>, which is similar to earlier  
 281 analysis (see below). The  
 282 very similar COSI-Corr (**Fig.**  
 283 **7b'**) and manually-derived  
 284 (**Fig. 7b''**) megaripple rates  
 285 (**Fig. 7e; Table 2**) illustrate  
 286 the robustness of our



**Figure 6.** Context for the Buzzel study site. (a) View of the Buzzel site in Context Camera (CTX) images, where dune crest flux vectors (color arrows) are projected along with the buffer area (white polygon) for Objective 3's whole dune field flux analysis. Dunes are downwind of steep NPLD scarps and the regional sand source to the northeast. (b) Regional view showing the field-of-view for (a) (white box) with Buzzel at the head of the Olympia Cavi reentrant. CTX mosaic colorized with MOLA elevation. (c) Examples of dune lee face positions during 3 Mars years (MY) and nearby megaripples (green polygons). (d) Oblique view looking downwind (white arrow in (a)) from a projected orthoimage. (inset) Closer view of dunes and megaripples in HiRISE color.

287 analysis. Although megaripple crests that are armored by coarse grains are probably impervious



**Figure 7.** Comparison of the sand fluxes at the edge of the “Buzzel” dune field. Also see Fig. 6 for context, Fig. S4 for mapping examples, Fig. S5 for sand rose diagrams, Fig. S6 for COSI-Corr details, and Table 2 for summary statistics. (a) Sand dune crest flux results. (a') Fluxes were evaluated at two time steps, spaced in time 3.8 and 5.7 EY. (b) Megaripple fluxes, which were estimated using two approaches: (b') automatic tracking of the bedforms with COSI-Corr, using a mask to select the intermediate scale bedforms and a constant half-height of 38 cm (corresponding to the average half-height estimated from the manual approach); and (b'') manual mapping of bedform crest traces, which allowed migration rates and wavelength-derived bedform half-heights to be estimated (time interval of 9.5 EY). (c, c') Sand fluxes of meter-scale dark ripples that were quantified using COSI-Corr (for DTR displacements) and a constant half-height of 12.5 cm is assumed (time interval of 22.6 days). (d) Circular plots showing the fluxes mean vectors ( $\text{m}^3 \text{m}^{-1} \text{yr}^{-1}$ ) and circular standard deviation intervals (dashed lines) for the bedforms and measurement techniques (in the case of the megaripples). (e) Flux comparisons for the Buzzel site bedforms that highlight the different modes of fluxes (fluxes distributions on the right), with megaripple's fluxes one and two orders of magnitude lower than DTR and dune crest fluxes, respectively.

288 to direct aeolian mobilization, copious amounts of DTR saltation events are available for creep  
289 transport. Note, megaripple rates are always lower than DTRs or dunes, indicating they don't  
290 contribute to total crest fluxes since they never or infrequently approach dune brinks. Instead  
291 megaripple populations are overtaken and occasionally buried by swifter dunes or DTR groups  
292 (**Animation S6-S7**). Active megaripples migration trends ( $216 \pm 50^\circ$ ) are closely aligned with those  
293 of dunes ( $226 \pm 31^\circ$ ), whereas migrating DTRs ( $247 \pm 34^\circ$ ) show a more westward trend (**Fig. 7d**,  
294 **S5**). Overall, it is estimated that the advancement of megaripples, reptation of DTRs, and dune slip  
295 face avalanches account for  $\sim 1\%$ ,  $\sim 10\%$ , and  $\sim 100\%$ , respectively, of the sand fluxes at the Buzzel  
296 dune field (**Fig. 7e**).

297 It is worthwhile to compare these results with non-polar megaripple sites. For example,  
298 dune crest fluxes at tropical latitudes in Nili Fossae and McLaughlin are  $\sim 3 \text{ m}^3 \text{m}^{-1} \text{yr}^{-1}$ , while fluxes  
299 derived for the megaripples in the same regions are two orders of magnitude lower ( $0.03\text{-}0.04$   
300  $\text{m}^3 \text{m}^{-1} \text{yr}^{-1}$ ) (Silvestro et al., 2020). Therefore, despite the higher magnitude of fluxes (more than  
301 double) and differing boundary conditions at the polar site, we observe a similar relation between  
302 the megaripples reptation and slip face advancement fluxes ( $\sim 1\%$ ).

303 Dark-toned ripple reptation fluxes in Nili Patera were found to correspond to 20% of the  
304 slip face fluxes ( $6.9 \text{ m}^3 \text{m}^{-1} \text{yr}^{-1}$ ; Bridges et al., 2012). Slower ripples at the Herschel crater dune  
305 field were estimated to have lower reptation fluxes ( $0.06 \text{ m}^3 \text{m}^{-1} \text{yr}^{-1}$ , see SM; Cardinale et al., 2016),  
306 which would equate to  $\sim 5\%$  of the bulk flux there ( $1.2 \text{ m}^3 \text{m}^{-1} \text{yr}^{-1}$ ; Vaz et al., 2017). A similar  
307 relationship is found for the Bagnold dune field located in Gale crater, where a reptation/bulk flux  
308 partition of 4% is estimated (Silvestro et al., 2016, 2020). Overall, the mentioned DTRs reptation  
309 fluxes represent 4-20% of the bulk sedimentary flux inferred from the slip face advancements, in

**Table 2.** Summary statistics for the compared bedforms' fluxes. The reported values correspond to a common area, located up to 1 km from the dune field edge at the Buzzel site (**Fig. 7, 6**).

	Mean flux azimuth (°)	Mean flux magnitude ( $\text{m}^3 \text{m}^{-1}\text{yr}^{-1}$ )	Circular variance	Circular STD (°)	N	Average flux ( $\text{m}^3 \text{m}^{-1}\text{yr}^{-1}$ )	Flux STD ( $\text{m}^3 \text{m}^{-1}\text{yr}^{-1}$ )
Dark-toned ripples	246.7	1.01	0.16	33.5	373172	1.2	0.77
Megaripples - COSI-Corr	215.6	0.04	0.31	49.8	27562	0.06	0.05
Megaripples - Manual	222.3	0.05	0.06	19.7	2758	0.05	0.05
Dune crest flux	226.4	7.73	0.13	30.7	9706	8.92	7.4

310 line with the 10% estimate for the Buzzel polar site. In addition, there appears to be a positive  
 311 correlation between bulk crest fluxes and the relative weight of DTR reptation fluxes, which will  
 312 be tested in the future.

## 313 **5.0 Discussion**

### 314 **5.1 Spatial heterogeneity of polar intermediate-scale bedforms**

315 North polar megaripples and TARs show spatial heterogeneity in their distribution  
 316 motivating the question – *why are these bedforms relatively abundant at some north polar sites,*  
 317 *but absent at others?* Survey results indicate aeolian megaripples are widespread in the north polar  
 318 region particularly for areas of higher dune density or sand volume (**Fig. 2a, 4**). If the identified  
 319 bedforms are truly composed of bimodal sand this indicates an abundant coarse-grained sand  
 320 population is present for the ergs – an interesting revelation considering the regional sand source.  
 321 The consensus view holds most regional sand is sourced from basal cavi units underlying the  
 322 NPLD (**Fig. S1**) (Byrne and Murray, 2002; Fishbaugh and Head, 2005; Tanaka et al., 2008). Based  
 323 on cross-bedding exposures, internal radar reflections, compositional links, and propensity to  
 324 produce sand the cavi units are widely agreed to be elements of a massive buried erg by an  
 325 expanding ice cap (Massé et al., 2010; Brothers et al., 2018; Nerozzi and Holt, 2019). The presence  
 326 of an ample coarse sand population, as inferred for megaripples based on their greater size and  
 327 bright crests, suggests the paleo-erg source was not mature enough to be dominated by fine, well  
 328 sorted sand. That is, a recycled sand source that has gone through repeated periods of  
 329 sedimentation (i.e., aeolian sandstone units) (Edgett et al., 2020) is more likely to be rich in fine

330 sand, as compared with a primary sand source (i.e., volcanoclastic units)(Kocurek and Lancaster,  
331 1999; Chojnacki et al., 2014).

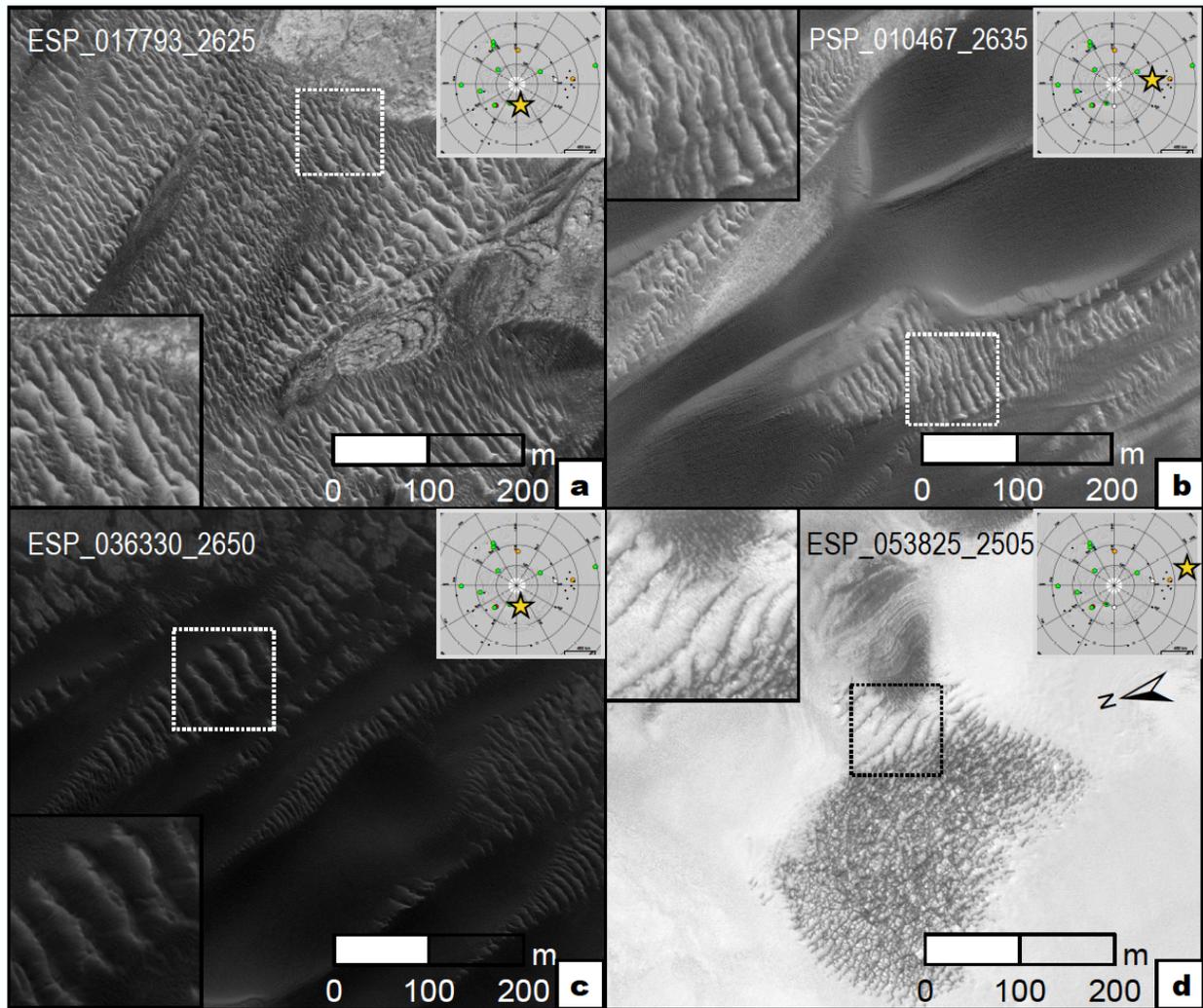
332 In contrast, there are certain sand transport corridors which lack both megaripples or TARs.  
333 For example, the low sand density barchans and ripples of the west Olympia Cavi reentrant (**Fig.**  
334 **2a**; 110°E, 81°N) are largely without intermediate-bedforms. Other inter-erg areas mapped with  
335 low to moderate sand coverage by Hayward et al. (2014) are similar (**Fig. 2a**). In these locations,  
336 scattered barchans or dome dunes migrate in low sediment supply conditions (**Fig. S1**), and are  
337 apparently deficient in a coarse sand population conducive to megaripple formation. These aeolian  
338 systems maybe ultimately sourced by a more mature (finer-grained) sand supply or have migrated  
339 far downwind of any accompanying coarser-sand megaripple population.

340 Interestingly, bedforms with characteristics commonly attributed to TARs (e.g. light-toned,  
341 transverse, >20 m in spacing) are generally absent in most polar regions except at the higher  
342 latitude NPLD-erg contact areas (**Fig. 2a, 4, 8**). The north polar TAR candidates identified  
343 generally appeared weathered, cracked, with rounded or “boxy” crests, or partially buried (as do  
344 some lower latitude examples (Sullivan et al., 2008; Chojnacki et al., 2018)), consistent with long-  
345 term inactivity (**Fig. 1a, 8**). Indeed, a detailed study in Scandi Cavi by Fenton et al. (2021)  
346 estimated a lower limit age of TAR-like bedforms there to be ~270 kyrs. Additionally, we suggest  
347 the stability and appearance for some polar TARs is most readily explained by an inter-granular  
348 ice component (see Section 5.2). Their close proximity to scarps (the likely regional sand source)  
349 and lack of mobility may suggest regional polar TARs did not migrate far after formation.

## 350 **5.2 Sand fluxes of polar megaripples and the seasonal cycle**

351 Prior work has suggested that north polar dune systems are more active than elsewhere –  
352 ~50% greater sand dune crest fluxes than on average for Mars ( $11.4$  vs.  $7.8 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$ ) (Chojnacki  
353 et al., 2019). The high magnitude of migration and flux rates of Buzzel’s DTRs, megaripples, and  
354 dunes (**Fig. 7**) would support this notion. It is noted, the cross-bedform comparison for Buzzel  
355 required the upwind (**Fig. 6**) and arguably most dynamic sections of the dune field to be analyzed  
356 – this was unavoidable due to data coverage. Nevertheless, this high level of bedform activity is  
357 somewhat surprising due to the short period (northern summer and autumn) for frost-free sediment  
358 availability (Hansen et al., 2013, 2015; Chojnacki et al., 2019). An important relevant question  
359 pertains to whether polar seasonal processes promote or retard megaripple activity. At a broadscale  
360 the unique surface-atmospheric volatile interactions found at the martian north pole and resulting

361 wind regime is likely a governing factor for the observed enhanced megaripple migration. The  
 362 north polar wind regime is dominated by off-cap katabatic ‘sublimation winds’, which are modeled  
 363 to be greatest in magnitude, consistent in direction, and perhaps more persistent throughout the  
 364 polar day during the late spring-summer than elsewhere on Mars (Massé et al., 2012; Smith and  
 365 Spiga, 2018). Winds are driven by seasonal and thermal effects of the retreating spring/summer  
 366 CO<sub>2</sub> ice and strong contrast between polar cap and erg surfaces in terms of elevation (~2 km-high),  
 367 temperature (23 K), and albedo (15-25%) (Howard, 2000; Smith and Spiga, 2018; Chojnacki et  
 368 al., 2019). These seasonally forced winds and occasional storm events (Wang and Fisher, 2009;



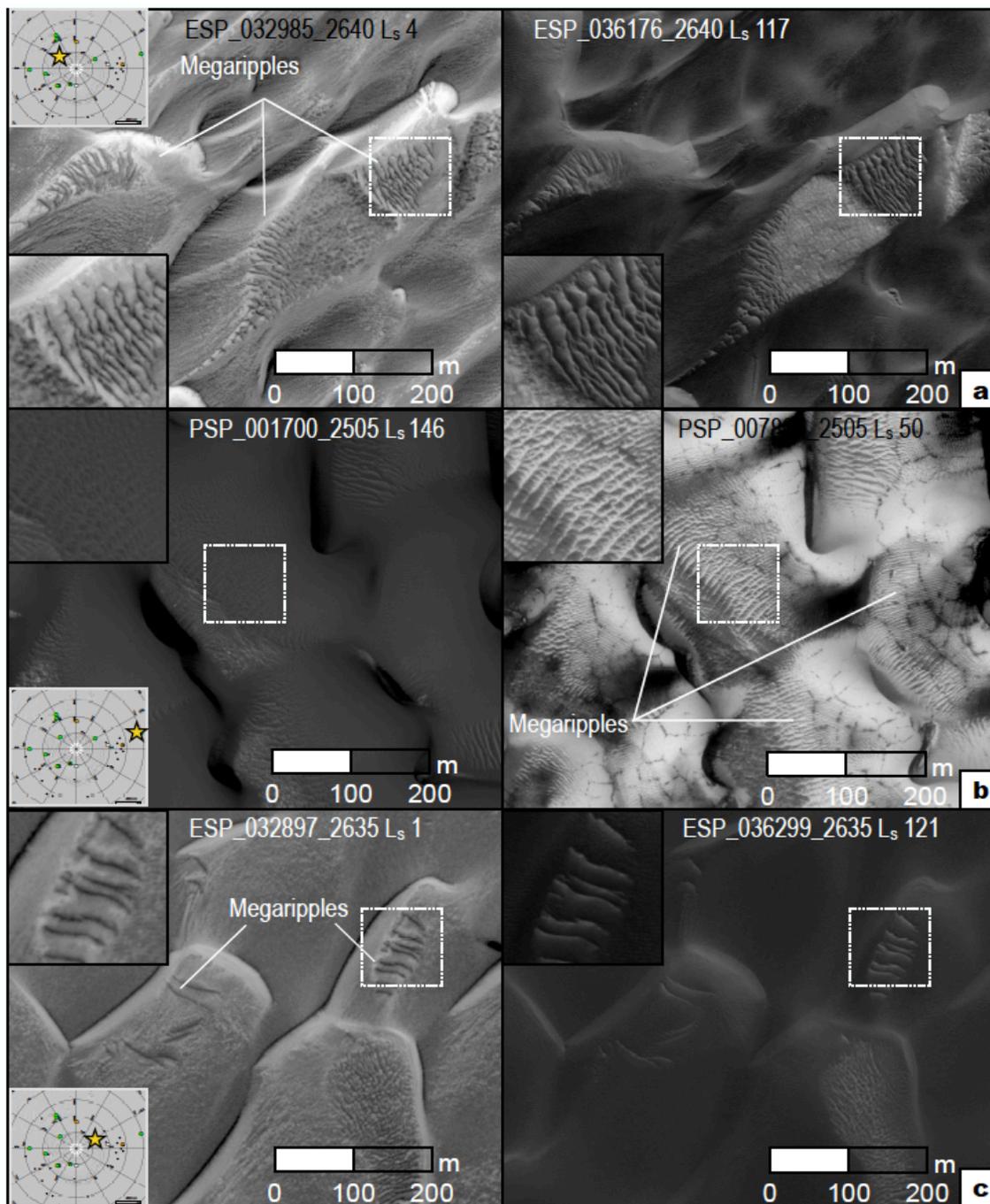
**Figure 8.** Polar erg sites with progressively more degraded TARs or megaripples (top left and working clockwise). All sites are for inactive bedforms that appeared weathered, cracked, with rounded or “boxy” crests, or partially buried. These static bedforms often show nearby mobile megaripples and DTRs without similar morphologic characteristics. (a) Chasma Boreale, (b) west Olympia Cavi, (c) Chasma Boreale, and (d) Louth crater. Inset maps show site locations (star) and HiRISE insets are 100-m-wide.

369 Calvin et al., 2015) appear to drive the high frequency megaripple activity in the region (**Fig. 2,**  
370 **7**).

371         What about more direct evidence of polar processes impacting bedform movement at a  
372 finer scale? For example, following summertime oversteepening by aeolian processes (Horgan and  
373 Bell, 2012) dune slip face alcove formation is seasonally constrained to the autumn/winter, further  
374 expanded during springtime frost sublimation, and estimated to contribute to 2-20% of dune  
375 movement (Hansen et al., 2015; Diniega et al., 2017). A similar process of seasonal fracturing and  
376 wasting of steeper megaripple lee-ward faces may lead to movement, even under frost veneers  
377 (**Fig. 9**). However, it is unclear that bulk megaripple displacements and their direction(s), which  
378 is well-correlated with that of the nearby bedforms (**Fig. 7d**), are dominantly caused by cryosphere  
379 processes. Most megaripple lee and stoss areas appear to be relatively symmetric and not  
380 substantially steeper on the lee-side, which might cause oversteepening and mini-alcoves.  
381 Although these features would be challenging to track, lee-side slumps or alcoves on megaripples  
382 are not clearly evident even when fully illuminated. Additionally, Buzzel's relative flux partitions  
383 between bedform classes are comparable to other equatorial dune fields, suggesting that primary  
384 aeolian transport modes (impact-driven creep and reptation + saltation) are driving most of the  
385 activity in the polar sites, instead of ice-related seasonal processes.

386         Instead, the cyclical deposition of CO<sub>2</sub>/H<sub>2</sub>O frost and ice has an important role in regional  
387 bedform stabilization over different time frames (Schatz et al., 2006; Brothers et al., 2018). Dark  
388 material with icy foresets, isolated dunes, cross-bedded strata and bounding surfaces have been  
389 identified in either cavi scarp units or interdune areas, which are interpreted as various components  
390 of an ancient aeolian sand sea related to past climate change (Ewing et al., 2010; Brothers et al.,  
391 2018; Nerozzi and Holt, 2019). Certain modern duneforms also show evidence for cross-stratified  
392 ice, partial burial by residual frost (**Fig. 1e, 8**), and thermal properties consistent with a shallow  
393 ice table (<1 m and as low as ~3 cm deep) (Putzig et al., 2014; Brothers and Kocurek, 2018). We  
394 suggest these cryospheric processes impact intermediate-scale bedforms as well and help explain  
395 the degraded morphology of some TAR-like bedforms. Polar TARs that are often characterized by  
396 weathered, occasionally pitted, or rounded crests that remain static despite being located in active  
397 sand pathways (**Fig. 1b, 8; Animation S8**). More extreme examples can be found of TARs buried  
398 in late season frost or perennial water ice (**Fig. 1c, 8b**). In these cases, volatile-related processes  
399 and any accompanying cohesion may have outpaced bedform mobility. An analogous process has

400 been described for lower-latitude immobile bedforms which display evidence for dry-condition  
 401 induration (e.g., cohesion, chemical weathering) and are thought to occur over long periods of  
 402 inactivity (Sullivan et al., 2008, 2020).



**Figure 9.** Seasonal changes between northern spring and summer for polar megaripples and dunes. All sites are for active megaripples. (a) Buzzel dunes in east Olympia Cavi reentrant, (b) Loath crater, and (c) West Olympia Cavi reentrant. Inset maps show site locations (star) and HiRISE insets are 100-m-wide.

403 In contrast to the static possibly ice-cemented polar TARs, megaripples in the same  
404 environment remain mobile over many polar winters even when temporarily buried then exhumed  
405 by swifter duneforms (**Animation S6-S7**). Whereas spring ice does not fill in megaripple troughs  
406 (estimated to be ~1 meter; e.g., **Fig. S3**), DTR areas appear to be smoothed over, suggesting  
407 decimeter-thick winter frost accumulation (**Fig. 9**). CO<sub>2</sub> frost is typically fully sublimated off  
408 sandy surfaces by late spring ( $L_s \sim 80-90^\circ$ ) (Hansen et al., 2013; Portyankina et al., 2013), possibly  
409 slightly earlier for sites like Buzzel where slip faces are orientated southward (Pommerol et al.,  
410 2013). DTRs and megaripple surfaces are able to respond to wind and regain mobility promptly  
411 around the northern summer solstice. While many of the boundary conditions are nearly identical  
412 for the adjacent populations of polar megaripples and TARs (e.g., seasonal cycle, wind regime,  
413 topography), sand availability for saltation/creep and inter-grain ice-content may be large factors  
414 in determining mobile vs. immobile.

## 415 6.0 CONCLUSIONS

416 This effort identified the presence, activity, and sand flux contribution of intermediate-  
417 scale aeolian bedforms across the north polar erg. The megaripple populations found at these  
418 locations were found to be migrating with dunes and dark-toned ripples when adequate data was  
419 inspected. Other key findings include the following:

- 420 • While megaripples are relatively minor components of terrestrial aeolian systems they  
421 are abundant on Mars and the north polar erg. Bedforms identified as TARs display  
422 characteristics consistent with inactivity (e.g., rounded or pitted crests) and are primary  
423 concentrated at the base of the polar layered deposit scarps and nearby erg areas. These  
424 (static) bedforms are adjacent to the regional sand source of the basal unit, which  
425 suggests polar TARs do not migrate far after formation.
- 426 • A lesser amount of polar aeolian systems, often on erg margins, lack megaripples but  
427 show widespread and mobile ripples and dunes (e.g., west Olympia Cavi reentrant).  
428 These areas are under low sediment supply conditions where widely-separated low  
429 sand volume barchan/dome dunes migrate. These areas may lack a particle size  
430 distribution conducive to megaripple formation (i.e., no coarse sand size fraction).
- 431 • Megaripples are highly active in the north polar region including NPLD reentrants (e.g.,  
432 Chasma Boreale), interior-erg areas, and polar craters (**Fig. 2**). The high level of  
433 observed activity seems to be associated with high sand fluxes of dunes, despite the

434 limited sediment availability when sandy areas are under autumn, winter, and spring  
435 CO<sub>2</sub> frost and ice (Hansen et al., 2013; Chojnacki et al., 2019).

- 436 • A focused analysis of an Olympia Cavi reentrant aeolian system estimated that the  
437 advancement of megaripples, saltation and reptation of DTRs, and dune slip face  
438 avalanches account for ~1%, ~10%, and ~100%, respectively, of the sand fluxes (**Fig.**  
439 **7**). To our knowledge DTR and dune rates are some of the highest yet documented on  
440 Mars, yet the flux partition between the various bedforms does not seem to differ from  
441 equatorial sites with lower sand fluxes.
- 442 • Polar megaripples yield fluxes that are two orders of magnitude lower than neighboring  
443 dunes, consistent with earlier work (Silvestro et al., 2020). While these bedforms do  
444 not show significantly greater migration rates or fluxes, activity does occur with a  
445 higher frequency across the polar ergs than lower latitudes, possibly due to the greater  
446 occurrence of high seasonal winds.
- 447 • Whereas seasonal ice contributes to some bedforms movement, such as dune slip face  
448 alcoves (Diniega et al., 2017), no evidence was found that cryospheric processes  
449 directly promoted megaripple migration. However, late spring-summer off-cap  
450 katabatic ‘sublimation winds’ along with polar storm induced winds are deemed major  
451 factors for the high levels of observed bedform activity.

452  
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461 tables, figures, and data tables (for Fig. S1-S6). All of the data used for this investigation can be  
462 found at the HiRISE website (<http://hirise.lpl.arizona.edu/>) or the Planetary Data System  
463 (<https://pds-geosciences.wustl.edu/missions/mep/index.htm>).

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