

A comprehensive picture for binary interactions of subaqueous barchans

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W. R. Assis¹, E. M. Franklin²

^{1,2}School of Mechanical Engineering, UNICAMP - University of Campinas,

Rua Mendeleev, 200, Campinas, SP, Brazil

Key Points:

- We identify five binary interactions of barchans and propose classification maps
- We show indications that an ejected barchan has the same mass of the impacting one
- We found that the asymmetry of the downstream dune is large in wake-dominated processes

Corresponding author: Erick M. Franklin, franklin@fem.unicamp.br

Abstract

We investigate experimentally the short-range interactions occurring between two subaqueous barchans. The experiments were conducted in a water channel of transparent material where controlled grains were poured inside, and a camera placed on the top acquired images of the bedforms. We varied the grain types (diameter, density and roundness), pile masses, transverse distances, water flow rates and initial conditions. As a result, five different patterns were identified for both aligned and off-centered configurations and we propose interaction maps that depend basically on the ratio between the number of grains of each dune, Shields number and alignment of barchans. In addition, we show experimental indications that an ejected barchan has roughly the same mass of the impacting one in some cases, and that in wake-dominated processes the asymmetry of the downstream dune is large. The present results shed light on the size regulation of barchans found on Earth and other planets.

Plain Language Summary

Barchans are crescent-shaped dunes that are often organized in dune fields, where binary interactions and collisions play a significant role in regulating their dynamics and sizes. Barchan collisions are frequent in many environments, such as Earth's deserts and on the surface of Mars, but their large time scales (the decade and the millennium for aeolian and Martian collisions, respectively) compared to the aquatic case (of the order of the minute) make subaqueous barchans the ideal object of study. Taking advantage of that, we performed experiments in a water channel of transparent material, where pairs of barchans were transported by the water flow while a camera acquired images of them. We found five different types of barchan-barchan interaction, and propose maps that provide a comprehensive classification for the short-range interactions of subaqueous barchans. In addition, we show that, in some cases, an ejected barchan has roughly the same mass of the impacting one, and that the perturbation of the flow caused by the upstream barchan generates large asymmetries in the downstream one. Our results represent a significant step toward understanding the barchanoid forms and size regulation of barchans found in water, air, and other planetary environments.

1 Introduction

The interaction between a fluid flow and a granular bed gives rise to different kinds of bedforms. Of particular interest are the crescent-shaped dunes, called barchans, that are formed under one-directional flow and limited amount of available grains, being encountered in different environments such as rivers, water ducts, Earth's deserts and other planetary environments (Bagnold, 1941; Herrmann & Sauermann, 2000; Hersen, 2004; Elbelrhiti et al., 2005; Claudin & Andreotti, 2006; Parteli & Herrmann, 2007). Although barchans may grow as isolated bedforms (Alvarez & Franklin, 2017, 2018), they are often organized in dune fields, where dune-dune interactions play a significant role in regulating their dynamics and sizes (Hersen et al., 2004; Hersen & Douady, 2005; Kocurek et al., 2010; Génois, Hersen, et al., 2013; Génois, du Pont, et al., 2013).

Over the past decades, several studies investigated the collisions and short-distance interactions of aeolian barchans based on field measurements (Norris & Norris, 1961; Gay, 1999; Vermeesch, 2011; Hugenholtz & Barchyn, 2012). Yet, because these measurements are based on aerial images, the time series for barchan collisions are usually incomplete given the long timescales of aeolian interactions (of the order of the decade), hindering a comprehensive understanding of barchan collisions. Because of their much faster scales (of the order of the minute), some studies investigated the interactions of barchans in water flumes and tanks (Endo et al., 2004; Hersen & Douady, 2005), from which different collision patterns were identified and their dynamics described. In addition, numerical simulations using continuum (Schwämmle & Herrmann, 2003; Durán et al., 2005;

68 Zhou et al., 2019) and simplified discrete models (Katsuki et al., 2011) could reproduce
69 some of the collision patterns, shedding light on the essential mechanisms involved. How-
70 ever, the simplifications present in those models precluded them from reproducing cor-
71 rectly all barchan interactions, failing to predict the correct split of dunes in some cases
72 and predicting soliton behavior in others.

73 By observing that a solitary barchan within a dune field is marginally stable, tend-
74 ing to grow or shrink once the stable size is disturbed, and the existence in nature of cor-
75 ridors of barchans, Hersen et al. (2004) proposed a model for the formation of corridors,
76 and Hersen and Douady (2005) showed that barchan collisions could be important for
77 the size regulation of barchans. In order to better understand the mechanisms behind
78 the formation of corridors with size-selected barchans, Durán et al. (2009) and Génois,
79 du Pont, et al. (2013) introduced simplified models based on sand flux balances and el-
80 elementary rules for barchan collisions. With such models, Durán et al. (2009) showed that
81 collisions are important for size regulation and inter-barchan spacing, while Génois, du
82 Pont, et al. (2013), by adjusting sand fluxes, obtained corridors of sparse and large or
83 dense and small barchans according to the balance between sand fluxes and collision types,
84 showing that sand distribution due to collisions organizes barchans in narrow corridors
85 of size-selected dunes. Bo and Zheng (2013), based on numerical simulations using a scale-
86 coupled model, found that the probability of barchan collisions varies with the flow strength,
87 grain diameter, grain supply and height ratio of barchans. They quantified the proba-
88 bilities for the occurrence of three different types of barchan collisions within a dune field
89 (merging, exchange and fragmentation-exchange, described next), but not how the col-
90 lision processes vary with the considered parameters.

91 Although many previous studies were devoted to barchan collisions, the problem
92 is still not completely understood and a general picture is lacking. The emerging pat-
93 terns, though present in both aeolian and aquatic environments, have not yet had all their
94 important parameters identified, so that universal expressions or maps for predicting the
95 results of collisions do not exist. The identification of collision patterns from the approach-
96 ing of subaqueous barchans until the end of the collisional process was performed by Endo
97 et al. (2004) in the case of aligned dunes for different mass ratios, and by Hersen and
98 Douady (2005) in the case of off-centered dunes for different transverse distances of cen-
99 troids of colliding dunes (referred to as impact or offset parameter), while Bo and Zheng
100 (2013) focused on the probabilities of barchan collisions in a dune field obtained from
101 numerical computations. However, how the diameter, density and roundness of grains,
102 flow strength and initial conditions affect the collision patterns remains to be investigated.
103 In addition, mass transfers between barchans during collisions are not completely un-
104 derstood.

105 In this Letter we investigate extensively the binary interactions, including binary
106 collisions, of subaqueous barchans. We carried out exhaustive measurements of the short-
107 range interactions between two barchan dunes, i.e., when their longitudinal separation
108 is of the order of the size of the upstream bedform, by varying the mass of initial piles,
109 their alignment (centered or off-centered), initial longitudinal separation, grain proper-
110 ties (diameter, density and roundness), flow strength and initial conditions (downstream
111 barchan already formed or to be developed), most of them affecting the patterns emerg-
112 ing from interactions. We identify five types of binary interactions for both aligned and
113 off-centered barchans, and show indications that an ejected barchan has roughly the same
114 mass of the impacting one in cases involving collisions with exchange of grains and that
115 in wake-dominated processes the asymmetry of the downstream dune is large. We pro-
116 pose a new classification for the binary short-range interactions of subaqueous barchans
117 that depends on the ratio between the number of grains of each dune, Shields number
118 and barchans alignment, shedding light on the size regulation of barchans in a dune field.

2 Materials and Methods

The experimental device consisted of a water reservoir, two centrifugal pumps, a flow straightener, a 5-m-long closed-conduit channel of transparent material and rectangular cross section (width = 160 mm and height $2\delta = 50$ mm), a settling tank, and a return line. A pressure-driven flow was imposed in the channel by means of the centrifugal pumps, and the flow followed the order just described. The channel test section was 1 m long and started 40 hydraulic diameters, $40 \times d_h$, downstream of the channel inlet, assuring a developed channel flow just upstream the bedforms, where $d_h = 3.05 \delta$ is the cross-sectional area multiplied by four and divided by the cross-sectional perimeter. With the channel previously filled with water, controlled grains were poured inside, forming a pair of bedforms in either aligned or off-centered configurations. By imposing a water flow, each bedform was deformed into a barchan shape and interacted with each other. We used different initial conditions, in which we placed a first pile and let it deform into a barchan dune before placing an upstream pile, or we let it deform in half-way a barchan dune before placing the second pile, or we placed two conical piles and let them deform together into barchan dunes, and the mass ratio of the piles, defined here as the mass of the upstream pile (impacting) divided by that of the downstream one (target), varied within 0.005 and 1. The initial longitudinal distance between bedforms was of the order of the diameter of the upstream pile, D , being within 0.22 and $3.6D$ between dune borders (smaller distance between dunes in the longitudinal direction), and, because the dune velocity varies with the inverse of its size (Bagnold, 1941), the mass of the impacting dune was always equal or lesser than that of the target dune. A camera placed above the channel acquired images of the bedforms and, therefore, we did not measure systematically the barchan height. However, based on reported values of the aspect ratio of barchans (Andreotti et al., 2002a) and our experimental observations, we estimate the crest heights as approximately 5 mm, i.e., 10 % of the channel height. The layout of the experimental device, a photograph of the test section, and microscopy images of the used grains are shown in the supporting information.

A total number of 123 tests were performed, for which we used tap water at temperatures within 22 and 30 °C and different populations of grains (not mixed): round glass beads ($\rho_s = 2500$ kg/m³) with $0.15 \text{ mm} \leq d \leq 0.25 \text{ mm}$ and $0.40 \text{ mm} \leq d \leq 0.60 \text{ mm}$, angular glass beads with $0.21 \text{ mm} \leq d \leq 0.30 \text{ mm}$, and zirconium beads ($\rho_s = 4100$ kg/m³) with $0.40 \text{ mm} \leq d \leq 0.60$, where ρ_s and d are, respectively, the density and diameter of grains. The cross-sectional mean velocities of water, U , varied between 0.226 and 0.365 m/s, corresponding to Reynolds numbers based on the channel height, $\text{Re} = \rho U 2\delta / \mu$, within 1.13×10^4 and 1.82×10^4 , where μ is the dynamic viscosity and ρ the density of the fluid. The shear velocities on the channel walls (base state), u_* , were computed based on measurements with a two-dimensional particle image velocimetry (2D-PIV) device (Franklin et al., 2014; Cúñez et al., 2018; Alvarez & Franklin, 2018) and found to follow the Blasius correlation (Schlichting, 2000), being within 0.0133 and 0.0202 m/s. By considering the fluid velocities applied to each grain type, the Shields number, $\theta = (\rho u_*^2) / ((\rho_s - \rho)gd)$, varied within 0.019 and 0.106, where g is the acceleration of gravity (see supporting information for a description of the PIV tests, estimated deviations in u_* and θ , and lists of all tested conditions).

3 Results

Five different patterns were observed as resulting from the short-range interaction, as can be seen in Figures 1 and 2, that show, respectively, snapshots of barchan interactions for the aligned and off-centered cases: 1) chasing (Figures 1a and 2a), when the upstream dune does not reach the downstream one. This pattern appears when the barchans have almost the same size, and the wake of the upstream dune, by increasing turbulent levels and creating channeling (Palmer et al., 2012; Bristow et al., 2018), promotes a larger erosion on the downstream dune, which then shrinks and moves faster (even if it receives

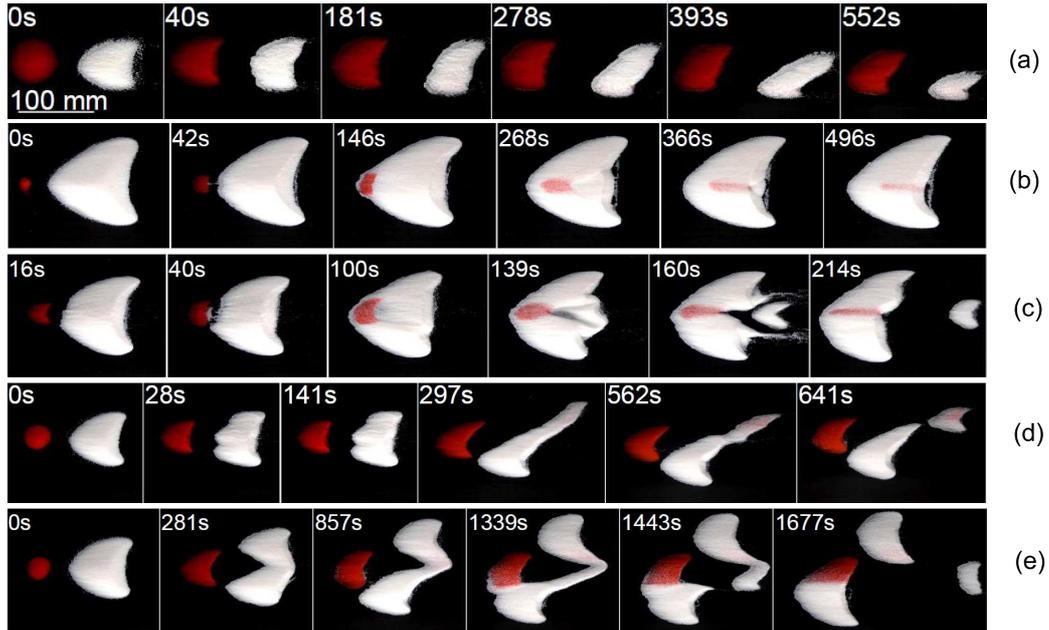


Figure 1. Snapshots of barchan interactions for aligned dunes. In the snapshots, the water flow is from left to right, the upstream pile consisting of red (darker) glass beads and the downstream pile of white (clearer) glass beads, and the corresponding times are shown in each frame. In Figure (a), $0.40 \text{ mm} \leq d \leq 0.60 \text{ mm}$ and in the remaining figures $0.15 \text{ mm} \leq d \leq 0.25 \text{ mm}$. (a) Chasing; (b) merging; (c) exchange; (d) fragmentation-chasing; (e) fragmentation-exchange, and they correspond to test numbers 61, 65, 36, 5 and 22 in the table of Fig. S23 of the supporting information, respectively.

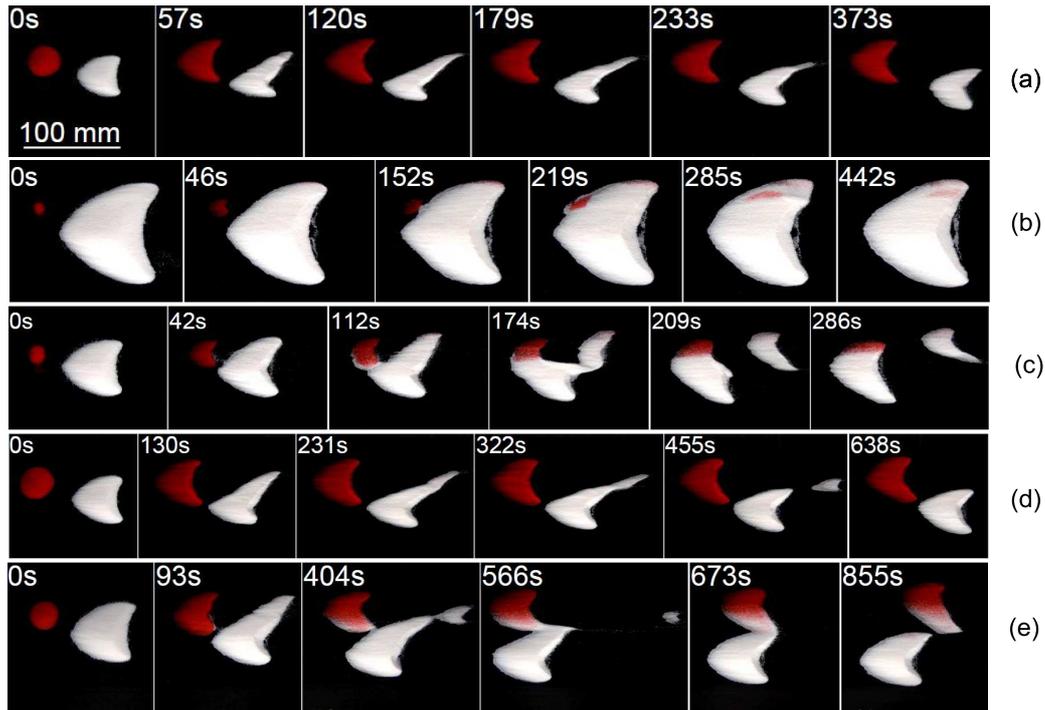


Figure 2. Snapshots of barchan interactions for off-centered dunes. In the snapshots, the water flow is from left to right, the upstream pile consisting of red (darker) glass beads and the downstream pile of white (clearer) glass beads of $0.15 \text{ mm} \leq d \leq 0.25 \text{ mm}$, and the corresponding times are shown in each frame. (a) Chasing; (b) merging; (c) exchange; (d) fragmentation-chasing; (e) fragmentation-exchange, and they correspond to test numbers 43, 38, 41, 31 and 5 in the table of Fig. S24 of the supporting information, respectively.

171 grains from the upstream barchan); 2) merging (Figures 1b and 2b), when the upstream
 172 dune reaches the downstream one and they merge; 3) exchange (Figures 1c and 2c), when,
 173 once the upstream dune reaches the downstream one, a small barchan is ejected and, be-
 174 ing the smaller one, outruns the other and migrates downstream. The first impression
 175 is that the impacting barchan traverses the target one, but the use of marked grains shows
 176 that there is mass exchange between them, as can be seen in Figures 1c and 2c. In some
 177 cases, depending on the sum of sizes of the impacting and target barchans, the ejected
 178 barchan is so small that it is close to the minimum size (Franklin & Charru, 2011) and
 179 spreads out just after being ejected; 4) fragmentation-chasing (Figures 1d and 2d), when,
 180 due to the wake of the upstream dune (Palmer et al., 2012; Bristow et al., 2018), in par-
 181 ticular just downstream the reattachment point of the recirculation region, the down-
 182 stream dune splits before being reached. Because the divided dunes are smaller than the
 183 upstream one, they outrun the upstream dune; and 5) fragmentation-exchange (Figures
 184 1e and 2e), when fragmentation as in (4) initiates, but, the upstream barchan being still
 185 faster than the splitting dune, the former reaches the latter. Once they touch, an off-center
 186 exchange occurs, and a small barchan is ejected. In the aligned configuration, the ejected
 187 barchan results from the interaction of an elongated horn with the remaining of the di-
 188 vided dunes, while in the off-centered configuration the ejected barchan is the smaller
 189 portion of the splitting dune. Finally, this redistribution of grains having finished, the
 190 smaller dunes are downstream and, therefore, three resulting barchans migrate without
 191 reaching each other. Movies showing all the five dune-dune interactions for both con-
 192 figurations and snapshots for other grain types are available as supporting information.

193 The presence of the five patterns in both aligned and off-centered configurations
 194 shows that variations of the offset (or impact) parameter, although influencing the con-
 195 ditions where patterns can appear, are not crucial for their appearance. Also, the mass
 196 ratio alone cannot regulate the appearance of all collision patterns, Endo et al. (2004)
 197 and Durán et al. (2005) having not found the five patterns for aligned dunes by vary-
 198 ing only their mass ratio. Endo et al. (2004) identified only the merging, exchange and
 199 fragmentation-chasing patterns (which they named absorption, ejection and split), and
 200 Durán et al. (2005), based on numerical simulations, the merging and exchange patterns
 201 (which they called coalescence and breeding), but the latter with a different behavior than
 202 our experimental observations. In addition, they found a pattern called budding, which
 203 could be equivalent to the fragmentation-exchange, but, in fact, is different, the target
 204 dune splitting only after the collision had happened, and also a solitary wave behavior,
 205 which is not observed experimentally. However, until now the different patterns emerg-
 206 ing from collisions have been described in terms of only the offset parameter and mass
 207 ratio (Katsuki et al., 2005; Génois, du Pont, et al., 2013; Génois, Hersen, et al., 2013).

208 We observed in our experiments that, in addition to these parameters, the fluid shear-
 209 ing and mass of each grain are also of importance, the latter, combined with the pile masses,
 210 being equivalent to the number of grains forming the piles. If, in one hand, the differ-
 211 ence in the number of grains (or, also, the mass ratio) gives the time scale for collision,
 212 on the other hand the total number of grains (or the sum of pile volumes) gives the to-
 213 tal size of the system, indicating if the resulting barchan is too large, with tendency to
 214 split because of instabilities of hydrodynamic nature (Andreotti et al., 2002a, 2002b; Charru,
 215 2006; Franklin, 2015). In addition, the flow strength and the size and density of grains
 216 are also related to hydrodynamic instabilities and to minimum sizes regulating the wave-
 217 length of bedforms and favoring the split of dunes or even their spread out (Andreotti
 218 et al., 2002b; Parteli et al., 2007; Franklin & Charru, 2011; Charru et al., 2013; Cour-
 219 rech du Pont, 2015), so that they also must be taken into account. For example, Khosronejad
 220 and Sotiropoulos (2017) showed that new barchans can be generated by a calving pro-
 221 cess on the horns of existing barchans, caused by the fluid shearing on the horn surface.
 222 Therefore, barchan collisions would be better described by the number of grains form-
 223 ing each pile, size and density of grains, flow strength and alignment of barchans, instead
 224 of only the mass ratio of piles and the offset parameter. Another aspect not investigated

225 in previous studies is the effect of initial conditions of bedforms on barchan collisions (tar-
 226 get barchan being initially a fully-developed barchan, a partially-developed barchan, or
 227 a conical pile). For the initial conditions, as well as the grain roundness, we did not ob-
 228 serve any significant difference in our experiments (see supporting information for snap-
 229 shots of barchan interactions with two conical piles as initial condition).

230 We propose that the short-range interaction patterns can be described by the off-
 231 set parameter, the Shields number, and the number of grains forming each pile. For the
 232 latter, the difference in the number of grains forming each pile, Δ_N , is proportional to
 233 the relative velocity of dunes, while the sum of those numbers, Σ_N , is proportional to
 234 the total size of the bedform once dunes have collided. We then introduce the dimen-
 235 sionless particle number:

$$\xi_N = \frac{\Delta_N}{\Sigma_N} \quad (1)$$

236 The Shields number is the ratio between mobile and resisting forces, linked to the
 237 fluid shearing and the grain weight, respectively, so that it takes into account the
 238 flow strength and the size and density of grains. Finally, the alignment of barchans
 239 is represented by the offset parameter σ (dimensionless), computed here as the
 240 transverse distance between the centroid of approaching barchans, η , divided by
 241 their average width: $\sigma = 2\eta/(W_U + W_D)$, where W_U and W_D are the widths of the
 242 upstream and downstream bedforms, respectively, and η is positive to the left of
 243 the target dune (with respect to the flow direction). Although we recognize three
 244 dimensionless groups, we decided to present all our data in two 2D maps in or-
 245 der to organize the patterns in the simplest and comprehensive way that we could
 246 find. Therefore, we plotted one interaction map for the aligned case (Figure 3a)
 247 and another one for the off-centered case (Figure 3b), where patterns are shown as
 248 functions of ξ_N and θ . In addition, for the off-centered case the map is parametrized
 249 by $\sigma < 0.5$ or $\sigma \geq 0.5$, which indicates if the the offset is relatively small or large,
 250 respectively. The number of grains forming each pile was considered as the ratio
 251 between the pile and grain masses.

252 Figures 3a and 3b show that the interaction patterns are relatively well organized
 253 by the ξ_N and θ groups, independent of the initial longitudinal separation between bed-
 254 forms, with transition regions between them where patterns are sometimes difficult to
 255 classify (their behavior in these regions is close to two patterns). Conscious of this dif-
 256 ficulty, we drew lines separating the different patterns, which we present in Figures 3c
 257 and 3d for the aligned and off-centered configurations, respectively. We drew such lines
 258 based solely on the experimental observations, and they consist in a tentative way to clas-
 259 sify the different patterns in θ vs. ξ_N maps. Although computation of those lines based
 260 on stability analyses or other analytical method remains to be done, we believe that the
 261 present maps may be useful for predicting the output of short-range barchan-barchan
 262 interactions under different conditions.

263 Based on image processing, we tracked the bedforms along the acquired images for
 264 each of the five patterns and identified some of their characteristic lengths. Because of
 265 approximately constant ratios between barchan dimensions (Hersen et al., 2002; Andreotti
 266 et al., 2002a), the projected area of a developed barchan multiplied by its height (around
 267 10% its width) is proportional to its volume, and, therefore, to its mass. However, in the
 268 present case barchans are being formed and deformed, interacting with each other, so
 269 that those relations are not completely valid. Conscious of that, we decided to analyze
 270 the projected areas of barchans as an indicator of the quantity of grains forming the dunes.
 271 Figure 3e presents the instantaneous values of the projected area of bedforms along time
 272 for the exchange pattern, and Figure 3f the evolution of the ratio between the lengths
 273 of the left and right horns (with respect to the flow direction), L_{hl} and L_{hr} , respectively.

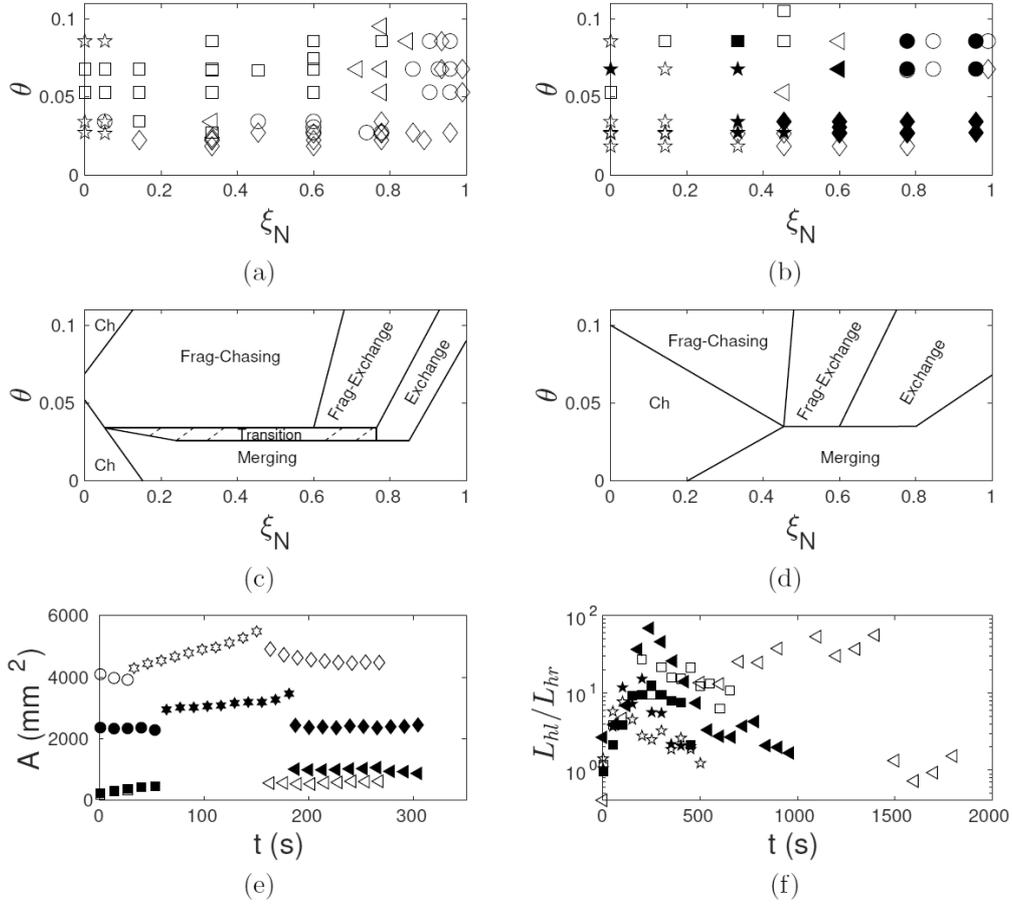


Figure 3. Figures (a) and (b): Patterns of barchan-barchan interactions as functions of ξ_N and θ for (a) aligned and (b) off-centered barchans. Stars, diamonds, circles, squares and triangles correspond to chasing, merging, exchange, fragmentation-chasing and fragmentation-exchange, respectively. In Figure (b), open symbols correspond to $\sigma < 0.5$ and solid symbols to $\sigma \geq 0.5$. Figures (c) and (d): Boundaries between different patterns for the aligned and off-centered barchans, respectively, where Ch stands for chasing and Frag to fragmentation. Figure (e): Area variation along time for the exchange pattern. Squares and circles correspond to the initial upstream (impact) and downstream (target) barchans, respectively, stars to the merged bedform, and diamonds and triangles to the merged bedform and new (expelled) barchan, respectively (tests 36 of Fig. S23 and 41 of Fig. S24 of the supporting information). Note that open squares are difficult to visualize in the graphic because they are at the same positions of solid squares. Fig (f): Ratio between the lengths of the left and right horns, L_{hl}/L_{hr} , of the downstream dune along time. Stars, squares and triangles correspond to chasing, fragmentation-chasing and fragmentation-exchange patterns, respectively (tests 61, 5 and 22 of Fig. S23, and 43, 31 and 5 of Fig. S24 of the supporting information). In Figs (e) and (f), open symbols correspond to the aligned and solid symbols to off-centered cases. All individual images that were processed to plot Figures (e) and (f) are available on Mendeley Data (<http://dx.doi.org/10.17632/jn3kt83hzh>)

274 We start by observing that the area of the upstream bedform increased in the be-
 275 ginning of all experiments because it was initially a conical pile, with a higher ratio be-
 276 tween its height and length, and, therefore, it spread out once the water flow was im-
 277 posed. While the upstream barchan was growing, the downstream one was already formed
 278 and lost grains by its horns without receiving much grains from the upstream bedform,
 279 so that its area decreased slightly in the beginning of each test. Figure 3e shows also that
 280 the area of the dune resulting from the collision increases along time due to its spread-
 281 ing, since just after collision the upstream dune (impact dune) climbs over the downstream
 282 one (target dune), as can be seen on movies available as supporting information. After
 283 that, a new born barchan is expelled with roughly the same area of the impact dune (see
 284 supporting information for a table showing the areas of impacting and expelled dunes
 285 of 15 tests). This indicates that the mass of the generated barchan is approximately that
 286 of the impacting one, though the constituent grains are not the same (Figures 1c and
 287 2c). Although this mass exchange of same value has been conjectured before (Vermeesch,
 288 2011), being even confounded with a solitary behavior in some cases (Schwämmle & Her-
 289 rmann, 2003), it had never been assessed from controlled experiments until now.

290 Finally, from Figure 3f we observe experimental evidence that the asymmetry of
 291 the downstream dune is large in wake-dominated processes (i.e., when the growth of one
 292 of the horns is due mainly to the fluid flow), the asymmetry being lower in the case of
 293 collision-generated asymmetries (not shown in Figure 3f, but presented in the support-
 294 ing information). This implies that the wake of upstream dunes (Palmer et al., 2012; Bris-
 295 tow et al., 2018), and not the collision itself, generates most of horns asymmetries. Al-
 296 though the origin of horns asymmetries has been studied previously (Parteli et al., 2014),
 297 it needs to be investigated further in the specific case of dune-dune interactions.

298 Although our experiments were limited to the subaqueous case, the resulting anal-
 299 ysis may be useful for predicting barchan-barchan interactions in other environments,
 300 such as Earth's deserts and on the surface of Mars. However, we expect differences re-
 301 lated to the larger quantities of grains involved in the aeolian and Martian dunes and,
 302 in particular, the trajectories followed by individual grains according to the state of the
 303 fluid. For the trajectories, grains move mainly by rolling and sliding and follow closely
 304 the fluid flow in the subaqueous case, being susceptible to small vortices and other small
 305 structures of the flow. This has been shown to be especially important for the grains mi-
 306 grating to the barchan horns (Alvarez & Franklin, 2018, 2019). When the fluid is a gas,
 307 grains move by saltation and reptation, and those in saltation follow basically a straight
 308 line in the main flow direction (Bagnold, 1941), being undisturbed by the small struc-
 309 tures of the flow. Discrepancies between the present analysis and the behavior in other
 310 environments are likely to occur, mainly for the wake-dominated processes, but where
 311 and when they occur, and to what extent, remain to be investigated.

312 4 Conclusions

313 In conclusion, subaqueous barchan-barchan interactions result in five different pat-
 314 terns for both aligned and off-centered configurations, being well organized in two maps
 315 as functions of ξ_N and θ and parametrized by σ . These maps provide a comprehensive
 316 and simple classification for the short-range interactions of subaqueous barchans and,
 317 although we have not analyzed the binary collisions in Earth's deserts and other plan-
 318 etary environments, given their long timescales, they may be useful for predicting the
 319 collisions of barchans in different environments. The present results represent a signif-
 320 icant step toward understanding the barcanoid forms, barchan asymmetries and size reg-
 321 ulation of barchans found in water, air, and other planetary environments.

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 327 mation and in Mendeley Data (<http://dx.doi.org/10.17632/jn3kt83hzh>).

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