Collision of barchan dunes as a mechanism of size regulation

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[1] Barchans are propagating crescentic dunes that form in arid regions where strong, unidirectional winds blow across a firm soil lightly covered with sand. Recently, solitary barchan dunes have been shown to be unstable towards sand flux variation either growing to form mega-dunes or shrinking and disappearing when perturbed from equilibrium. However, observations of large corridors of barchan dunes in the field suggest that these bedforms are stable over long periods of time. Since dunes' migration rates are inversely proportional to their size, barchans of different size must collide and these collisions may be crucial in maintaining the stability of dunes in nature. Here, we first explain the unstable behavior of solitary barchans and then illustrate, using down-scaled physical experiments, the qualitative dynamics of binary collisions. A stability analysis, inspired by these experiments, suggests that collisions may indeed regulate the size of barchans migrating in a corridor by redistributing sand from large dunes to smaller ones. **Citation:** Hersen, P., and S. Douady (2005), Collision of barchan dunes as a mechanism of size regulation, *Geophys. Res. Lett.*, *32*, L21403, doi:10.1029/2005GL024179.

1. Introduction

[2] Barchans are aeolian, crescentic sand dunes that are shaped by a unidirectional wind on firm ground. Their crescentic shapes as well as their high migration rates have motivated many investigations, starting with the far-reaching work of *Bagnold* [1941]. From then on, geologists, and more recently physicists, have considerably improved our description of aeolian bedforms and in particular of barchans by using field investigations [*Bagnold*, 1941; *Pye and Tsoar*, 1990; *Cooke et al.*, 1993; *Finkel*, 1959; *Hastenrath*, 1967; *Parker*, 1999; *Kocurek et al.*, 1992; *Sauermann et al.*, 2000], theoretical and numerical tools [*Werner*, 1995; *Werner and Kocurek*, 1997; *Nishimori et al.*, 1997; *Kroy et al.*, 2002; *Andreotti et al.*, 2002; *Hersen*, 2004], and laboratory experiments [*Mantz*, 1978; *Hersen et al.*, 2002; *Endo et al.*, 2004a; *Hersen*, 2005]. These studies have produced a fairly accurate description of solitary barchans. Here, we combine this knowledge with a new analysis to understand the long-time behavior of assemblies of barchans that are often found on the field: the corridors of barchans (see Figure 1). Such corridors are formed by many barchans of roughly uniform sizes and can extend several tens of kilometers downwind. As a matter of fact, trying to understand basic properties of these corridors from what is known about barchan dynamics leads to surprising conclusions.

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[3] The speed of barchan, c is inversely proportional to its height, h, through the relation: $c \sim q/h$, where q is the sand flux [*Bagnold*, 1941; *Andreotti et al.*, 2002], so that smaller barchans migrate faster. This implies that from an initial corridor of heterogenous barchans, size segregation should occur with time due to the relative differences in migration rate. This separation of dunes with respect to their sizes should keep increasing with time. It has also been shown that barchans are unstable towards sand flux variations [*Hersen et al.*, 2004]. This instability can be understood as follows: sand escapes the dunes only from the horns' tips, where no slip-face can trap sand grains. As the slip face appears only if the local slope is too steep, its formation in the lee side depends mainly on the local height rather than the height of the dune, h. This means that the total width of the horns, w_h, does not change significantly with h and thus with the total width, w. Moreover, in the wake of the horns, the output flux is concentrated such that it is close to the carrying capacity of the wind, i.e., it is nearly saturated [*Sauermann et al.*, 2000]. Therefore, the total output flux, $\Phi_{out} = q_s w_h$, does not depends strongly on the size of a barchan. This qualitative argument is supported by numerical simulations of *Hersen et al.* [2004], which show that $\Phi_{out} = q_s w_h = q_s(\alpha w + \Delta)$, with $\alpha \sim 0.05 \ll 1$, $\Delta \sim 4.6$ m and q_s the saturated sand flux. Consequently, if a barchan at equilibrium slightly increases its width, the total influx Φ_{in}, becomes larger than the total output flux $\Phi_{out} = q_s w_h$ and, as a result, the dune grows. This instability suggests that barchans in a corridor should either grow into mega barchans or shrink and disappear.

[4] Both conclusions are in obvious contradiction with basic field observation as shown on Figure 1. This paradox comes from the incorrect assumption that barchans in a corridor behave like solitary barchans. In particular, the density and the distribution of sizes of barchans in the corridor of Figure 1 suggest that collisions of dunes occur frequently. In fact, collisions should play a role in both the mass balance dynamics of barchans (and therefore their natural unstable behavior) and the spatial distribution of barchans with respect to their sizes since small barchans might merge with larger dunes. To make progress in understanding the stability of barchan corridors, it is helpful to first study a simple collision of two barchans. A typical collision event is depicted in Figure 1b but because of the size and speed of the involved barchans (between ~30 m and ~150 m and a difference of speed of a few meters a year) the whole process will take several decades.

2. Laboratory Experiments

[5] An alternative to aerial photographic analysis is the use of laboratory under-water experiments [*Allen*, 1968; *Mantz*, 1978; *Endo et al.*, 2004a]. We have designed a table-

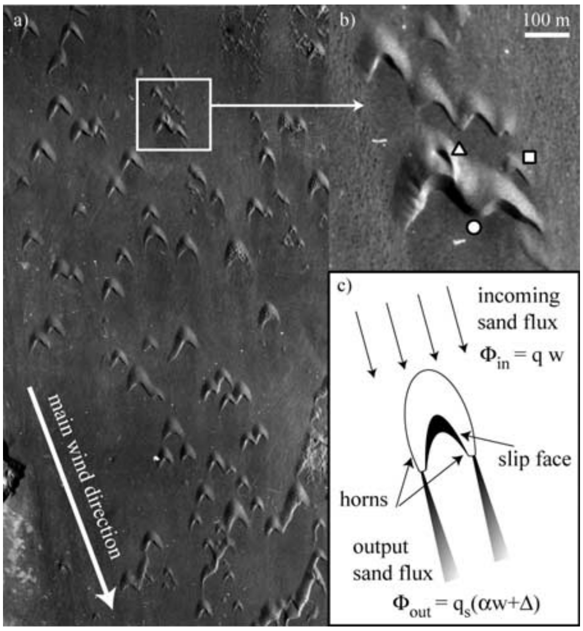

Figure 1. Aerial photograph taken from a corridor of barchans in the region between Tarfaya and La'ayoune in South Western Morocco. Barchans of various size coexist and interact with each other while migrating downwind. (b) The large double barchan (○) is under collision by a much smaller barchan as shown by the presence of a shaded area (the slip face of the small barchan). Another collision (at an earlier stage) can be observed in the center right part of the picture (□). The upwind barchans (△) will finally catch up to the double barchan and produce another collision. (c) A typical barchan catches sand on its back and loses it only from the tip of its horns.

top experiment based on the asymmetric motion of a tray under water to reproduce the effect of a strong unidirectional flow able to shape a conical sand pile into a migrating barchan [*Hersen et al.*, 2002; *Hersen*, 2005]. Barchans are centimeter-scale and form on short timescales, allowing us to conveniently explore subaqueous barchan dynamics. Moreover, it has been shown that these subaqueous dunes have the same morphology and dynamics than aeolian barchans once rescaled by a fluid density correction [*Hersen et al.*, 2002; *Hersen*, 2005]. Collisions were studied by creating a target dune, $\in_t$ ($w \sim 5$ cm, $c \sim 0.03$ mm/s) and an impacting dune upwind, $\in_i$ ($w \sim 1$ cm, $c \sim 0.08$ mm/s). Because $c \sim q/h$, the smaller dune will catch up the larger one in approximately one hour only. Contrary to previous studies, [*Endo et al.*, 2004b; *Schwämmle and Herrmann*, 2003; *Katsuki et al.*, 2005], we focused on the realistic case of off-center collisions rather than on the peculiar situation of centered collisions. Several experiments (see Movie 1 in the supplementary material)[1] have been done with the same set of two dunes and varying the impact parameter δ (see Figure 2). The ratio between $\in_i$ and $\in_t$ was chosen so as to observe a collision: too small a ratio results in absorption of the smaller dune, while sub-equal sizes do not produce a collision over a short timescale.

[6] The general mechanism of a collision can be outlined from these experiments. When the two dunes are close enough, $\in_t$ is locally eroded by the wake of $\in_i$ because of the high shear stress in the vicinity of the reattachment point behind the sheltered area of $\in_i$ [*Endo et al.*, 2004b]. As the collision is not symmetric, the eroded sand is preferentially directed through the horn of $\in_t$ located downstream of the wake of $\in_i$. Evidence for this process comes from observation of the sand leak trace - that often gives rise to very small and fast barchans - or by the presence of an elongated horn. This horn would eventually detach from $\in_t$ and transform itself into a barchan while the two upwind barchans merge and form a symmetric barchan. It may also lead to more than one emitted barchans (see Figures 2a, 2c, and 2d). To gain further insight, dunes were made with green and red glass beads to examine the exchange of mass during the merging process (see Movie 2 in the supplementary material). Figure 3 reveals the mixing of the two dunes: $\in_i$ literally pushes away a part of $\in_t$, and after a complex transient state it merges with the unperturbed red part of $\in_t$ to form a symmetric barchan, while a horn of $\in_t$ separates from the newly shaped barchan.

[7] These experiments suggest that a simple conceptual picture of barchan collisions involves an exchange of mass between $\in_t$ and $\in_i$: the target barchan gains a proportion ϵ of the volume of the incoming dune while losing one (or several) barchan(s) of total mass $(1 - \epsilon)$ times the mass of the incoming dune. Even if the situation is quantitatively different for aeolian dunes, qualitative evolution should remain the same. We now apply the insights gained from examination of binary collisions to resolve the paradox of the existence of barchan corridors in the case of an ideal corridor of barchans.

3. Collisions as a Regulation Mechanism

[8] Let us consider the case of a corridor where all barchans are much larger than the minimal size of barchans so that the height, the width and the length of barchans are almost proportional [*Sauermann et al.*, 2000]. In that case the width, w, can be used to describe the equilibrium state of a particular barchan. Let us further assume that all the barchans have exactly the same width w_0, the same volume $V_0 = bw_0^3$ and the same speed $c_0 = aq_s/w_0$. Typical values for $a \sim 50$, $b \sim 0.011$ and $q_s \sim 66$ m^2/*year* have been derived in a previous work [*Hersen et al.*, 2004] with the help of field measurements in the region of Tarfaya, Southern Morocco. We define N_0 the number of barchans per unit area, and q_0, the sand flux in the corridor which is chosen so that barchans are at equilibrium, each dune losing as much sand as it gains. We further assume that the sand flux seen by the dunes is always homogeneous, which is a reasonable assumption as long as N_0 is not too large. Accordingly, this ideal corridor is in an equilibrium state.

[9] Let us assume that one particular dune increases its size slightly to $w = w_0(1 + \eta)$. This particular dune, $\in_t$, is now out of equilibrium and its volume changes because the incoming sand flux, $\Phi_{in} = q_0 w$, now exceeds the sand flux escaping from its horns, $\Phi_{out} = q_s(\alpha w + \Delta)$. In the mass balance, we now have to take into account the influence of smaller, faster upwind dunes exchanging mass with $\in_t$ by

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL024179.

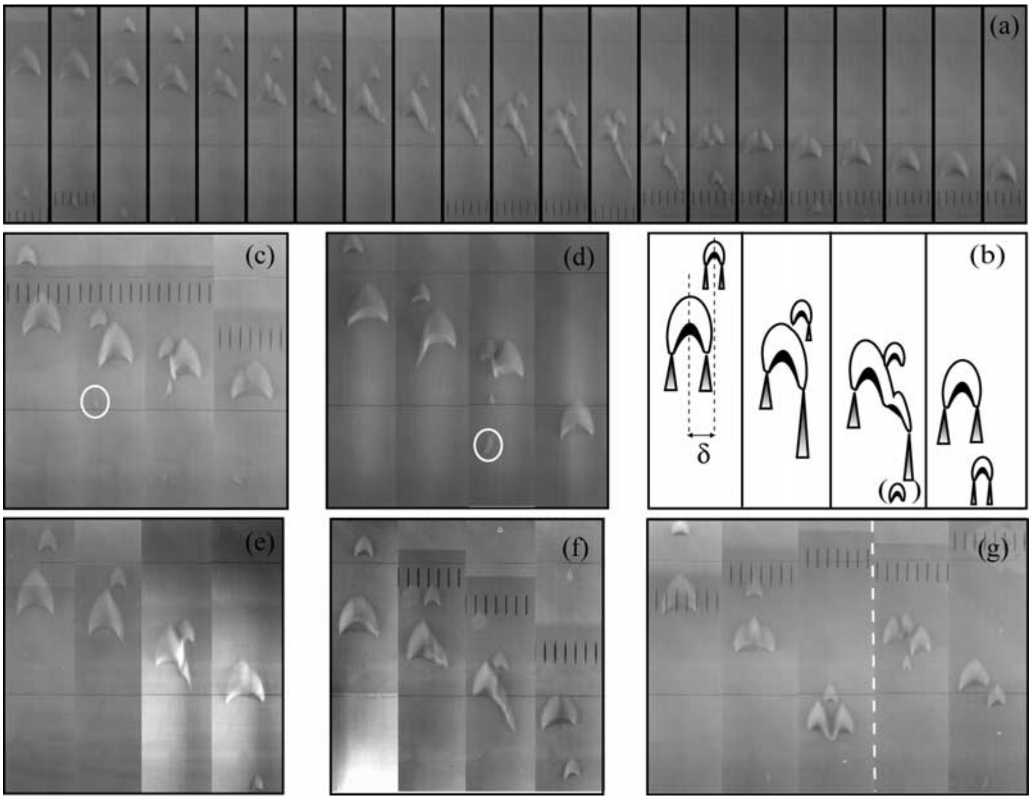

Figure 2. Experimental observations of binary collisions with different impact parameters. Initially $\in_i$ is 1 cm wide, and $\in_t$ is 5 cm wide. The impact parameter δ is defined as the distance between the center of mass of the two dunes normalized by half the total width. (a) Detailed representation of a collision with $\delta \sim 0.22$. Notice the elongated horn and the emission of barchans. (b) Main features of an off center collision. (c) $\delta = 0.54$; (d) $\delta = 0.5$; (e) $\delta = 0.44$; (f) $\delta = 0.18$; (g) $\delta = 0.02$. White circles in Figures 2c and 2d show that several barchans can be emitted. See supplementary materials for videos of the collisions.

way of collisions. An upwind dune will collide $\in_t$ during the time dt if it is closer than $dL = \Delta c dt$, where Δc is the difference of speed between the two dunes. The number of such dunes is given by the area $dL(w + w_0)$ times the density of dunes N_0 (see Figure 4). Using the expression of the speed, c, as a function of w, this leads to the number of collision per unit of time:

$$\frac{dn_{coll}}{dt} = N_0(w + w_0)\frac{aq_s(w - w_0)}{ww_0}. \quad (1)$$

Therefore, the mass balance for this particular dune becomes:

$$\frac{dV}{dt} = (q_0 - q_s\alpha)w - q_s\Delta + \epsilon V_0 N_0(w + w_0)\frac{aq_s(w - w_0)}{ww_0} \quad (2)$$

where ϵV_0 describes the gain of volume of the target barchan during the collision event. For $\epsilon < 0$, the emitted barchan is larger than $\in_i$ and $\in_t$ shrinks. Using the fact that at equilibrium, $q_0 = q_s(\alpha + (\Delta/w_0))$, we can derive the equation for the evolution of the perturbation η:

$$\tau_v\dot{\eta} = \left(1 + \frac{(2+\eta)}{2(1+\eta)}\frac{\epsilon N_0}{N_c}\right)\frac{\eta}{(1+\eta)^2} \quad (3)$$

with $\tau_v = 3bw_0^3/q_s\Delta$ and $N_c = \Delta/(2w_0^3ab)$. Linearizing the above equation around $\eta = 0$, it follows that the growth rate $\sigma = \dot{\eta}/\eta$ depends on ϵ as:

$$\tau_v\sigma = \left(1 + \frac{\epsilon N_0}{N_c}\right) \quad (4)$$

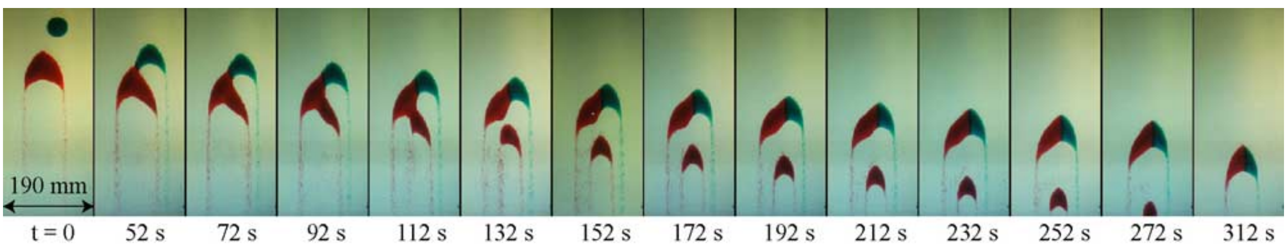

Figure 3. Binary collision made with two dunes of different colors. The target dune is made with red glass beads of 250 μm and the impacting dune with green glass beads of the same size. This shows the sand exchange process during a collision event. See supplementary materials for a video of the collision.

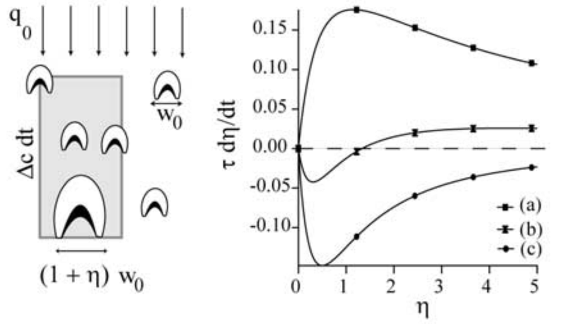

Figure 4. Evolution of the perturbation growth rate of barchan width, $\dot{\eta}$, with respect to the perturbation amplitude η. Curve a, $|\epsilon|N_0 = 0.4N_c$ the perturbation is unstable; curve b, $|\epsilon|N_0 = 1.4N_c$: if the perturbation is small the barchan recovers its previous width, w_0; curve c, $|\epsilon|N_0 = 2N_c$: the perturbation is always canceled out by collisions.

Thus, the perturbation is progressively erased by the successive collisions of barchans if the density of dunes is larger than a critical density:

$$N_0 > -\frac{1}{\epsilon}N_c \qquad (5)$$

This simple case shows (see Figure 4) that if during the collision $\in_i$ gives more mass than $\in_t$ loses ($\epsilon > 0$) then the situation is still unstable and $\in_t$ keeps on growing. However if the transfer of mass is globally from $\in_t$ to the newly created barchan ($\epsilon < 0$), then the barchan $\in_t$ can recover its previous size. This would happen if the density of dunes is high enough: to counterbalance the natural increase in size by the sand flux, a high rate of collisions is needed. The sign of ϵ is difficult to extract from our experiments (because of the null input flux condition). However, recent numerical work suggests that $\epsilon < 0$ [*Duran et al.*, 2005]. The mechanism of regulation is still valid even if several barchans are emitted: in such a case, those barchans will either be absorbed by a larger dune if they are too small compared to the average size [*Schwämmle and Herrmann*, 2003] or will increase their mass by successive collisions, leading again to a "stable" corridor.

4. Discussion and Conclusion

[10] However simple the previous model is, it shows that collisions of barchans can explain the long-term stability of corridors. Of course, a corridor is a place of much more complicated interactions (inhomogeneities of the sand flux, fluctuation of the wind in both intensity and directions, influence of the topography) which should also play a significant role. Further developments are needed to gain a complete picture of the dynamics of barchan corridors. We nevertheless believe that collisions of barchans, by redistributing the excess of mass between different barchans, play a crucial role in regulating the natural tendency of barchans to be unstable. This redistribution, by regulating the size of barchans, also explains why the distribution of size does not seem to evolve with the distance downwind. The experiments also outline other important consequences of collisions in a corridor. First, small barchans are often created during a binary collision and this may explain why small barchans can be found everywhere in a corridor. This observation suggests that the nucleation of barchans may be intimately related to the mechanics of collision. Second, these experiments show that collisions can be invoked to explain the asymmetry of some barchans (as suggested by *Clos-Arceduc* [1969]) rather than the effect of changes in the wind direction. As a matter of fact, during a collision event, one horn can become longer than the other (see Figure 2). From this point of view the double crescentic barchans shown in the inset of Figure 1 could be the result of an old collision event. Finally, given that ϵ should depend on the impact parameter, δ, we expect a size dispersion to appear in a field, and to be maintained because of collisions. Measuring the size dispersion of dunes in a corridor of barchans and the density of barchans, N_0, should help to determine ϵ and N_c and to test this approach. This mechanism of size selection by collisions is an exciting avenue of research both for physicists and geologists.

[11] **Acknowledgment.** Many thanks are due to Douglas Jerolmack for his help concerning this work and for very enlightening discussions about barchans and bedforms dynamics.

References

Allen, J. R. L. (1968), *Current Ripples: Their Relation to Patterns of Water and Sediment Motion*, Elsevier, New York.
Andreotti, B., P. Claudin, and S. Douady (2002), Selection of dune shapes and velocities. part 1: Dynamics of sand, wind and barchans, *Eur. Phys. J. B*, *38*, 341–352.
Bagnold, R. A. (1941), *The Physics of Blown Sand and Desert Dunes*, CRC Press, Boca Raton, Fla.
Clos-Arceduc, A. (1969), *Essai d'Explication des Formes Dunaires Sahariennes*, *Etud. Photo Interpretation*, vol. 4, 66 pp., Inst. Geogr. Natl., Paris.
Cooke, R., A. Warren, and A. Goudie (1993), *Desert Geomorphology*, UCL Press, London.
Duran, O., V. Schwämmle, and H. Herrmann (2005), Breeding and solitary wave behavior of dunes, *Phys. Rev. E*, *72*, 021308.
Endo, N., H. Kubo, and T. Sunamura (2004a), Barchan-shaped ripple marks in a wave flume, *Earth Surf. Processes Landforms*, *29*, 31–42.
Endo, N., K. Taniguchi, and A. Katsuki (2004b), Observation of the whole process of interaction between barchans by flume experiments, *Geophys. Res. Lett.*, *31*, L12503, doi:10.1029/2004GL020168.
Finkel, H. J. (1959), The barchans of Southern Peru, *J. Geol.*, *67*, 614–647.
Hastenrath, S. L. (1967), The barchans of the Arequipa region, southern Peru, *Z. Geomorphol.*, *11*, 300–331.
Hersen, P. (2004), On the crescentic shape of barchan dune, *Eur. Phys. J. B*, *37*, 507–514.
Hersen, P. (2005), Flow effects on the morphology and dynamics of aeolian and subaqueous barchan dunes, *J. Geophys. Res.*, doi:10.1029/2004JF000185, in press.
Hersen, P., S. Douady, and B. Andreotti (2002), Relevant length scale for barchan dunes, *Phys. Rev. Lett.*, *89*, 264301.
Hersen, P., K. H. Andersen, H. Elbelrhiti, B. Andreotti, P. Claudin, and S. Douady (2004), Corridors of barchan dunes: Stability and size selection, *Phys. Rev. E*, *69*, 011304.
Katsuki, A., H. Nishimori, N. Endo, and K. Taniguchi (2005), Collision dynamics of two barchan dunes simulated by a simple model, *J. Phys. Soc. Jpn.*, *37*, 507–514.
Kocurek, G., M. Townsley, E. Yeh, K. Havholm, and M. L. Sweet (1992), Dune and dunefield development on Padre Island, Texas, with implications for interdune deposition and water-table-controlled accumulation, *J. Sediment. Petrol.*, *62*(4), 622–635.
Kroy, K., G. Sauermann, and H. J. Herrmann (2002), Minimal model for aeolian sand dunes, *Phys. Rev. E*, *66*, 031302.
Mantz, P. A. (1978), Bedforms produced by fine, cohesionless, granular and flakey sediments under subcritical water flows, *Sedimentology*, *25*, 83–103.
Nishimori, H., M. Yamasaki, and K. H. Andersen (1997), A simple model for the various pattern dynamics of dunes, *J. Mod. Phys. B*, *12*, 256–272.

Parker, G. S., Jr. (1999), Observations regarding the movement of barchan sand dunes in the Nazca to Tanaca area of southern Peru, *Geomorphology*, *27*, 279–293.
Pye, K., and H. Tsoar (1990), *Aeolian Sand and Sand Dunes*, CRC Press, Boca Raton, Fla.
Sauermann, G., P. Rognon, A. Poliakov, and H. J. Herrmann (2000), The shape of the barchan dunes of southern Morocco, *Geomorphology*, *36*, 47–62.
Schwämmle, V., and H. J. Herrmann (2003), Solitary wave behaviour of sand dunes, *Nature*, *426*, 619–620.
Werner, B. T. (1995), Eolian dunes: Computer simulations and attractor interpretation, *Geology*, *23*, 1107–1110.
Werner, B. T., and G. Kocurek (1997), Bedform dynamics: Does the tail wag the dog?, *Geology*, *25*, 771–774.

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