Formation and stability of transverse and longitudinal sand dunes

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ABSTRACT

The shape of dunes depends on the history of wind regimes and sand availability. In deserts exposed to winds from two different directions but with comparable magnitude, dunes are found to be linear ridges, which are either perpendicular or parallel to the mean wind direction, depending on the angle between the two wind directions. These dunes, respectively observed for small and large angles between winds, are called transverse and longitudinal dunes. In both cases, their large width (hundreds of meters) and evolution time scale (years) strongly limit the investigation of their dynamics and thus our understanding of such structures. Here we show that, under water, similar structures can be obtained but at much smaller space and time scales. Performing controlled experiments together with numerical simulations, we highlight the physical mechanisms at play in the formation and long-term evolution of these structures. We show in particular that, while longitudinal dunes are stable and extend in time, transverse dunes are unstable. They evolve into wavy ridges and eventually break into barchans if the sand supply is too low. This fundamental difference is understood through the study of single sand piles and bars exposed to two winds. In the case of a large angle between winds, a sand pile grows a finger pointing in the average wind direction and transforms into a longitudinal dune. Such an elongation does not occur for a small angle where a sand pile evolves into a barchan. These results explain the morphological differences between straight and long longitudinal dunes and sinuous transverse dunes, while giving keys to infer the wind history or pattern state of development from the observation of dune shapes in the field.

INTRODUCTION

Sand dunes are the geomorphological record of eolian processes. Their shape, if not altered by topography, cohesion, or vegetation, depends on local conditions of sand availability and wind strengths and directions (Bagnold, 1941; Cooke et al., 1993; Pye and Tsoar, 1990). Barchans, crescent-shaped dunes, are observed when sand is scarce and when the wind is unidirectional (Bagnold, 1941). Large star-shaped dunes are found where winds alternatively blow in many directions (see the GSA Data Repository[1]). When winds have two dominant directions, dunes are found to be long linear ridges whose trend may be perpendicular, oblique, or parallel to the long-term sand transport direction (Cooke et al., 1993; Pye and Tsoar, 1990). Dunes with an oblique trend are observed when the transport of sediment in one direction dominates the one in the other direction (Rubin and Hunter, 1987; Rubin and Ikeda, 1990; Werner and Kocurek, 1997; Kocurek and Ewing, 2005). When both magnitudes are comparable, the trend only depends on the angle between the two transport directions (Rubin and Hunter, 1987; Rubin and Ikeda, 1990). If this angle is small, sinuous ridges form perpendicularly to the average transport direction. For large angles, straight ridges extend for tens of kilometers parallel to the mean transport direction (Fig. 1). Following Rubin and Hunter's approach, we name these dunes after their genetic term, being transverse and longitudinal dunes respectively (Rubin and Hunter, 1985). Both transverse and longitudinal dunes may be found widely in numerous Earth deserts such as Rub al-Khali in Saudi Arabia, or in Namibia, but also on Mars or Titan (Data Repository) (Pye and Tsoar, 1990; Cooke et al., 1993; Malin et al., 1998; Lancaster, 2006; Lorenz et al., 2006; Rubin and Hesp, 2009). The strong correlation between shapes of dunes and wind properties suggests that the observation of dunes may shed light on past and present meteorological conditions at work in these deserts. However, besides the domain of existence of transverse and longitudinal dunes (respectively for angles

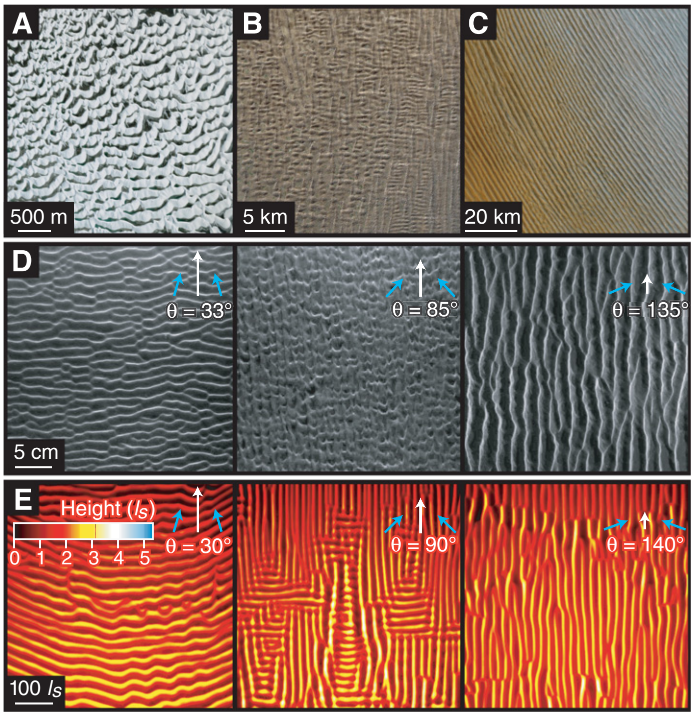

Figure 1. Transverse and longitudinal dunes. A: Transverse dunes degenerated into barchanoid ridges (White Sands, United States, GPS: 32.786°N, 106.264°W, from Google Earth). B: Mixed pattern showing both longitudinal and transverse structures (Taklamakan desert, China, GPS: 38.69°N, 78.703°E, from Google Earth). C: Longitudinal dunes extending coherently for several tens of kilometers (Rub al-Khali desert, Saudi Arabia, GPS: 18.19°N, 47.629°E, from Google Earth). D: Experimental dunes growing from a flat sand bed blown by two winds. For θ = 33°, transverse dunes form. For θ = 135°, longitudinal dunes form, while for θ = 85°, a transition state shows a square pattern, superposition of the two possible states. Images were taken after 60 periods. From left to right, dunes are, on average, 0.35, 0.65, and 1.2 mm high. E: Transverse, mixed, and longitudinal dunes obtained from numerical simulations. Profiles were taken after 75 periods. The scaling length l_s scales with the drag length (see the GSA Data Repository [see footnote 1]). Both approaches successfully reproduce the field patterns observed on A, B, and C.

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[1]GSA Data Repository item 2010144, a description of the numerical model, details of the experiments, and movies of formation of both longitudinal and transverse dunes, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

smaller or bigger than 90° for symmetric wind regimes), which has been confirmed experimentally by Rubin and Hunter (1987) and Rubin and Ikeda (1990), not much is known about the physical mechanisms at play in the genesis and the evolution of linear ridges (Livingstone et al., 2006). This is mainly due to the difficulty in investigating dynamics of such large dunes in the field.

METHODS

The physics of sand dunes relies on the coupling of sediment transport by a fluid and the modification of the flow by the bedform. This makes any flat sand bed destabilize and transform into dunes (Bagnold, 1941; Kroy et al., 2002). The most unstable wavelength, which sets the minimum size for a dune, scales with the turbulent drag length l_d, proportional to the grain size times the density ratio between grains and the surrounding fluid (Hersen et al., 2002; Kroy et al., 2002). For sand grains in air, this minimum size is a few meters long, which makes laboratory studies of eolian dunes challenging. However, it reduces by a factor of 1000 when considering water as the surrounding fluid. As a result, dunes form at a much smaller scale (millimeters) underwater. Moreover, characteristic timescales being size-dependent, they are also drastically downscaled. Thus, subaqueous dunes are perfect candidates to investigate dune dynamics in the laboratory. Our experimental setup consists of moving a plate covered with sand in a water tank. It is moved quickly in one direction, smoothly stopped, and then brought back to its initial position, slowly enough to prevent grain motion (this sequence equals one "stroke"). In the moving frame, and for every stroke, the sand bed is subject to a unidirectional flow/wind that destabilizes it. This approach has been successfully used to study barchans (Hersen et al., 2002). Here the sand bed is now periodically exposed to winds of equal strength but with two distinct directions, by alternately rotating the plate by an angle θ (–θ) every two strokes (four strokes equals one "period"). The number of strokes or wind strength does not affect qualitatively the results as long as sand patterns are large enough to integrate the bimodal wind regime (Data Repository). A typical experiment counts hundreds of periods (each of four strokes) and lasts several days. Typically, a centimeter-scale barchan travels over a distance equivalent to its size in 50 strokes (3 h) in the experiment, while this takes a month for a meter-scale eolian barchan in the south Morocco desert (Hersen et al., 2004). Sand bed evolution is recorded using a top view camera. Furthermore, using a laser sheet, three-dimensional profiles are acquired at given time points, giving a full quantitative record of the sand bed topography (Data Repository). We investigate the genesis and the stability of transverse and longitudinal dunes through the study of localized sand piles, single linear structures, or extended flat sand beds subject to a symmetric bimodal wind regime without any sand supply. The experimental study is strengthened by numerical simulations based on a 2D + 1 minimal model for sand dunes (Data Repository) (Hersen, 2004; Kroy et al., 2002).

RESULTS AND DISCUSSION

Starting from flat sand beds, we performed a set of experiments and numerical runs with θ ranging from 0° to 180°. As can be seen in Figures 1 and 2, transverse dunes form for θ ≤ 90°, while longitudinal dunes are observed when θ ≥ 90°. The underwater experiment and the numerical code successfully reproduce the patterns observed in nature and in previous works (Movies DR1–DR4 in the Data Repository) (Rubin and Hunter, 1987; Rubin and Ikeda, 1990; Werner and Kocurek G., 1997; Kocurek and Ewing, 2005; Parteli and Herrmann, 2007). The set of solved equations in the numerical code includes only one unstable process, which generates and amplifies crests perpendicularly to the blowing wind. This supports

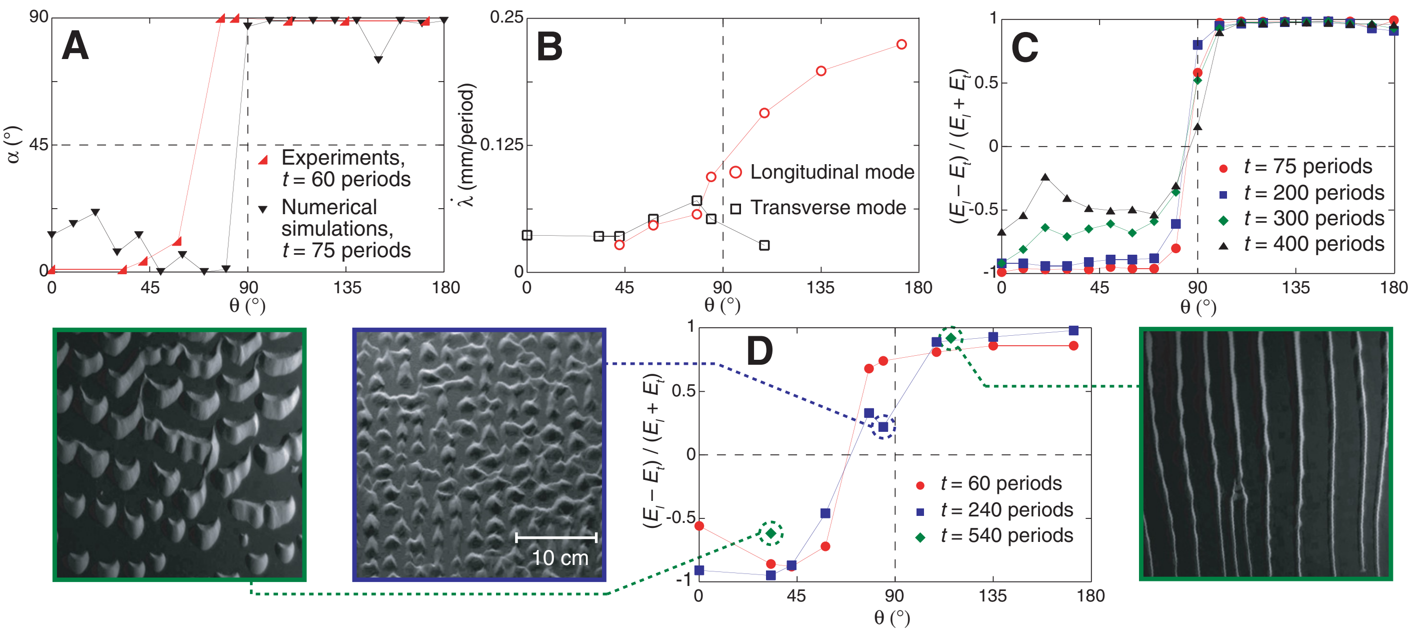

Figure 2. Formation and long-term evolution of transverse and longitudinal dunes. Starting from a 1-mm-thick flat sand layer, either transverse or longitudinal dunes form, depending on the angle θ between the two wind directions. A: Direction α, with respect to the mean wind direction, in which wave vectors hold the most energy (from the computation of the magnitude squared of the two-dimensional Fourier transform of sand bed height profiles). This plot reveals the strong binary character of dune orientation. B: Initial growth rate, $\dot{\lambda}$, of the dominant wavelength in the experiments as a function of θ. C–D: Time evolution of the two modes for numerical simulations (C) and experiments (D). E_t represents the energy of the transverse mode, sum of the amplitude squared of wave vectors making an angle between –45° and 45° with the mean wind direction. E_l is the corresponding energy of the longitudinal mode. The energy ratio $(E_l - E_t)/(E_l + E_t)$ measures the balance between the two modes. For small timescales only either the transverse or the longitudinal mode is observed, so the ratio is respectively close to –1 or 1. But while longitudinal mode is stable in time, transverse dunes are unstable. For θ value bigger than 90°, the whole energy always remains in the longitudinal mode (1). For θ value smaller than 90°, the energy ratio increases with time, and the preferential orientation of the pattern vanishes. Experiment snapshots are 31 cm across. From left to right, dunes are 3.5 mm, 2.5 mm, and 1.3 mm high on average. The mean wind direction is from bottom to top.

the idea that no secondary flow is needed to explain the genesis of longitudinal dunes (Cooke et al., 1993; Pye and Tsoar, 1990). The initially flat sand bed first exhibits structures that are perpendicular to each wind direction, a superposition of the two patterns expected for each single wind. In this symmetric regime of winds, dunes progressively align perpendicularly ($\theta < 90°$) or parallel to the mean wind ($\theta > 90°$). At the transition, a square pattern is observed, showing both transverse and longitudinal structures. As shown by Rubin and Hunter (1987), the final orientation of structures maximizes the orthogonality between the structure and sand fluxes. Indeed, if considering that a structure growth rate is, at first order, proportional to the sand flux perpendicular to its crest, a simple stability analysis explains this alignment and the mixed pattern observed at the transition, when $\theta = 90°$ (Data Repository). Dunes are either perpendicular or parallel to the mean wind direction (Fig. 2A). Therefore, the θ value cannot precisely be inferred from the orientation of the pattern. In experiments, the transition is sharp and occurs around 80° for early times and shifts to 90° with time (Figs. 2A and 2D). This suggests that longitudinal dunes are initially dominant over transverse ones when $\theta \approx 90°$. Indeed, we measured that the dominant wavelength growth rate is larger for longitudinal dunes ($\theta > 90°$) than for transverse ones at the beginning of the experiments (Fig. 2B). Besides this coarsening dynamic, transverse and longitudinal dunes evolve very differently in the long term. While longitudinal dunes remain straight, transverse dunes quickly transform into barchanoid ridges, which break into numerous propagating barchans when the nonerodible bottom is reached (Figs. 2C and 2D) (Endo et al., 2004). Therefore, long-term solutions are either barchanoid fields or straight longitudinal dunes. To explain this stability difference, we remove complex dune interactions within a dune field and look at isolated dunes emerging from simple structures: a conical sand pile (Fig. 3) and a sand bar (Fig. 4).

As expected, under a unidirectional wind ($\theta = 0°$), a conical pile transforms into a barchan (Bagnold, 1941) (Movie DR9). Wind erosion on the back of the sand pile leads to the formation of a crest perpendicular to the wind direction and so to the formation of a slip face downwind. The wind boundary layer separates at this crest, forming a recirculation bubble. According to mass conservation, the thin sides of the pile propagate faster than its top (Bagnold, 1941; Hersen et al., 2002), turning the pile into a crescent shape with elongated arms. The dune stops elongating and migrates as a whole when the mass lost at its horns is balanced by a lateral mass transfer, due to the effect of gravity on sand motion at the surface of the dune (Hersen et al., 2002). This scenario remains valid for small θ, although the pile first exhibits two crests, perpendicular to each wind direction, joining at the top of the pile. This leads to a barchan-like dune with a smaller slip face and smaller, fatter horns (Fig. 3A). When $\theta > 90°$, the two initial slip faces progressively merge into a single crest. In contrast to the barchan case, the resulting crest is aligned with the mean wind and advection direction, which makes a finger grow at the crest tip. The sand pile then strikingly transforms into a longitudinal dune (Fig. 3C; Movie DR10). This is a key result to understand the formation of longitudinal dunes and their fundamental stability difference with transverse ones.

When a longitudinal bar is subject to two winds with $\theta \ll 90°$, both wind directions are almost aligned with the bar and destabilize it. Crests form perpendicularly to the bar like they would for a flat sand bed. The instability develops and the bar quickly breaks into aligned barchans (Fig. 4A; Movie DR7). The small wind components perpendicular to the bar do not lead to any destabilization because of the pronounced aspect ratio of the bar in this direction. Similarly, for a transverse bar when $\theta \gg 90°$, both winds are again almost aligned with the bar, and crests develop perpendicularly to it. But now each crest is aligned with the mean wind direction and extends by growing a finger like it would for an isolated sand pile. The transverse bar turns into an array of longitudinal dunes (Fig. 4B; Movie DR6). This reveals that, under scarce-sand conditions, longitudinal dunes and barchans (but not transverse dunes) are attractors for large and small θ, respectively (Werner, 1995), whatever the initial conditions. Indeed, a longitudinal bar is stable for large θ, whereas a transverse bar breaks into barchans of roughly similar sizes in its genesis domain, i.e., for small θ (Figs. 4C and 4D; Movies DR5 and DR8). In both cases, the small components of the wind parallel to the bar slightly destabilize it along its length. For a transverse bar and a small θ, this deformation leads to velocity differences between valleys (faster) and hills (slower), which break the bar into barchans of roughly similar size as it migrates downwind (i.e., perpendicular to the bar). On the contrary, for a longitudinal bar and a large θ, the height modulations remain of small amplitude. Indeed, there is a stabilization mechanism as we highlighted before: Isolated sand patches aligned to the mean wind direction reconnect through growing fingers.

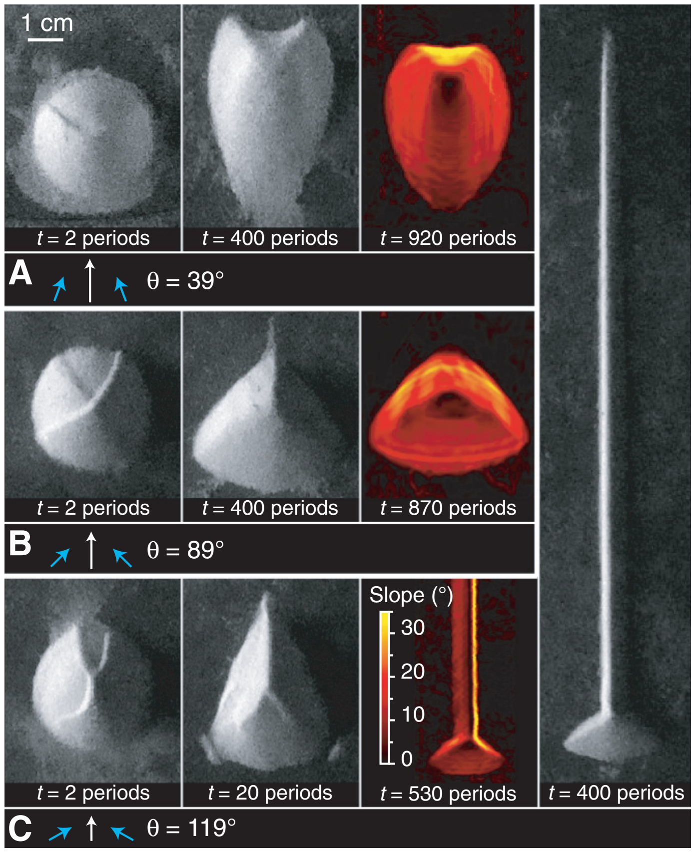

Figure 3. Extension of a sand pile into a longitudinal dune. Piles have an initial mass of 5 g. Scale of pictures is displayed on panel A. Colored pictures show the local slope on the dune (from three-dimensional reconstruction). Color code is shown on panel C. A: θ = 39°; the pile is shaped into a barchanoid. One can see the slip face between the two arms. The arms and the slip face of the barchanoid are smaller than the ones of a barchan, i.e., when θ = 0° (Data Repository [see footnote 1]). The scanned dune is 4.1 mm high. B: θ = 89°; two crests perpendicular to each wind direction are superimposing before the sand patch transforms into a chestnut-shaped dune. The scanned dune is 3.95 mm high. C: θ = 119°; the two slip faces merge and a finger grows. The final structure looks like a single longitudinal dune. The slip face is observed on one side then on the other successively, depending on the blowing wind direction (Movie DR10 in the Data Repository). The dune was scanned at the end of the two strokes of the wind blowing from left to right. The dune base here is 1.2 mm high, while its extending finger is 0.7 mm high.

CONCLUSIONS

Our study explains why longitudinal dunes are coherent over tens of kilometers, whereas transverse dunes often look like barchanoid ridges

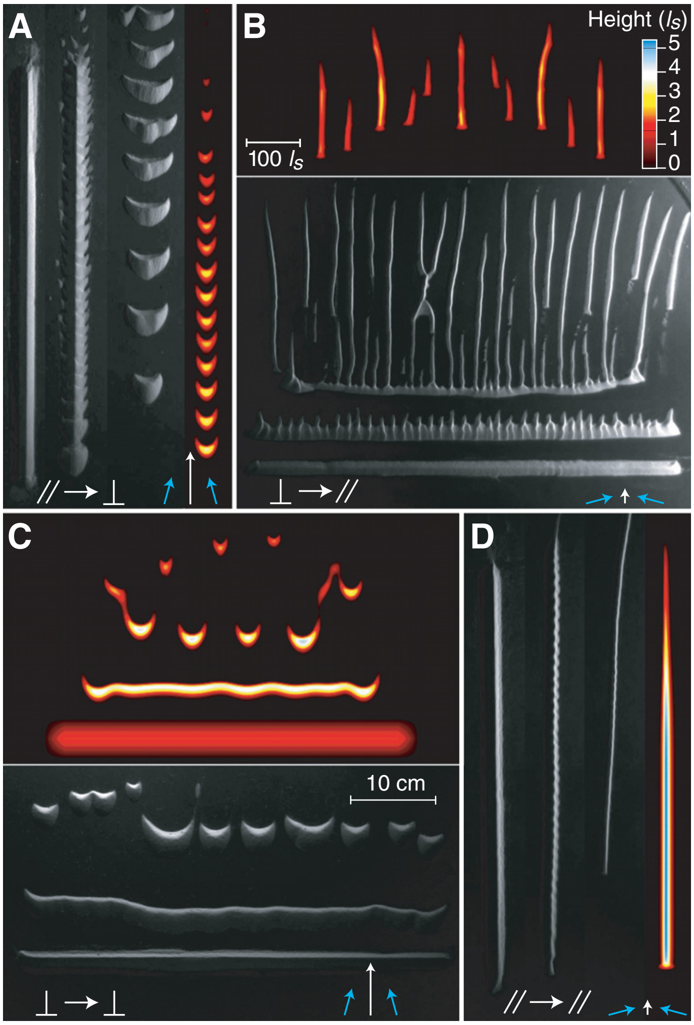

Figure 4. Stability of idealized linear sand ridges under bimodal wind regimes. Scales of experiment snapshots and numerically modeled height profiles (in color code) are displayed on panels C and B respectively. A: Longitudinal dune stability for a small θ. Experiment: θ = 25°, pictures taken after 0, 60, and 350 periods. Numerical simulation: θ = 30°, profile taken after 100 periods. The sand bar turns into barchanoids (Movie DR7 in the Data Repository [see footnote 1]). B: Transverse dune stability for a large θ. Experiment: θ = 145°, pictures taken after 0, 20, and 90 periods. Numerical simulation: θ = 150°, profile taken after 200 periods. The sand bar turns into longitudinal dunes (Movie DR6). C: Transverse dune evolution for a small θ. Experiment: θ = 25°, pictures taken after 0, 70, and 400 periods. Numerical simulation: θ = 30°, profiles taken after 0, 200, and 400 periods. The transverse dune breaks into barchans (Movie DR5). D: Longitudinal dune evolution for a large θ. Experiment: θ = 145°, pictures taken after 0, 150, and 420 periods. Numerical simulation: θ = 150°, profile taken after 250 periods. The longitudinal dune remains stable (Movie DR8).

that break when the nonerodible bottom is reached (Fig. 1). Indeed, such sinuous shapes are intrinsic to the evolution of transverse dunes, even without any other effect at play, such as meteorological fluctuations or dune interactions. It also explains why barchans rather than transverse dunes are observed when sand is scarce, while sand availability does not play such a role on longitudinal dunes (Cooke et al., 1993). More generally, our study provides us with records of dune morphological history. Looking at the evolution of elementary dunes (cones or bars), we highlighted mechanisms (Figs. 3 and 4) and transitory shapes that can be observed in real sand dune fields (Fig. 1; Data Repository). This approach opens the possibility of extracting wind regimes history and dune field state of development from a single pattern observation.

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