Coexistence of two dune growth mechanisms

C. Narteau *Université Paris Cité, Institut de Physique du Globe de Paris, CNRS, France – narteau@ipgp.fr*
S. Courrech du Pont *MSC, Université Paris Cité, CNRS, France – sylvain.courrech@u-paris.fr*

ABSTRACT: We review field measurements, subaqueous laboratory experiments and numerical simulations documenting dune growth, shape and alignment under multidirectional flow conditions. In zones of infinite sand supply, dune patterns select the orientation for which the sand flux perpendicular to the crest is maximum. In zones of low sand availability, dunes tend to align with the direction of the resultant sand flux at the crest. In the first case, periodic dunes grow in height from the available sedimentary resource in the interdune area. In the second case, dunes elongate by developing a finger-like structure on the non-erodible ground. These two dune growth mechanisms are modelled and quantified from the dynamic interactions between topography, flow and sediment transport to predict dune orientation, wavelength, migration speed and growth rate. This framework can provide new information about flow conditions and sediment properties in remote places where dunes exhibit different orientations, especially in marine environments.

1 INTRODUCTION

In all environments in which they occur, in arid deserts, underwater, or on other planets, dune fields often exhibit complex shapes combined with ridges of variable orientation. According to local sediment transport and flow properties, it is therefore essential to understand the origin of such diversity by documenting the mechanisms of dune growth based on elementary physical processes.

Dunes have been primarily classified according to their shape considering both sand availability and flow directional variability (Wasson & Hyde, 1983). In aeolian research, the wind directional variability is usually measured by the RDP/DP dimensionless parameter (Fig. 1). It is the ratio between the resultant drift potential (RDP, the norm of the mean sand flux vector) and the drift potential, DP (the mean of the norms of the individual sand flux vectors). In zones of low sand availability under nearly unidirectional winds (i.e., for high, close to one, RDP/DP-values), crescentic barchan dunes propagate on a non-erodible ground (Fig. 1). Under the same wind conditions, barchanoid and transverse linear dunes form where sand availability increases. They all exhibit a strong asymmetry between a gentle upstream slope and a slip face in the lee. On the other hand, network dunes and star dunes are observed in major depositional centers exposed to wide multidirectional wind regime (i.e., where the RDP/DP-value tends to zero). For intermediate wind directional variability, linear dunes develop. Given the seasonal changes in wind direction on Earth, these linear dunes are widespread in terrestrial sand seas, but their alignments, symmetry and slopes vary greatly depending on the sand availability and the wind regime.

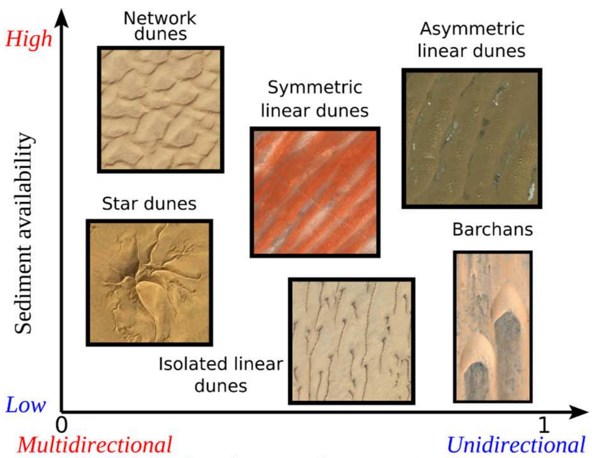

Figure 1. Classification of dune shape according to wind directionality and sediment availability (modified from Wasson & Hyde, 1983).

Dunes have also been classified according to their orientation. The crest lines of barchan dunes are approximately perpendicular to the resultant transport direction, whereas, by definition, the interlaced arms of star dunes have no unique orientation (Zhang et al., 2012). For linear dunes, Hunter et al. (1983) used the angle Φ between their crestlines and the resultant transport direction on a flat sand bed to describe them as longitudinal ($\Phi \leq 15°$), oblique ($15° < \Phi < 75°$) or transverse ($\Phi \geq 75°$).

A significant breakthrough in understanding the relationships between bedform orientation and flow regime was the work of Rubin & Hunter (1987). When considering a bidirectional flow regime, they experimentally showed that subaqueous bedforms select the orientation for which the sum of the normal to crest components of the two transport vectors reaches its maximum value. Thus, they introduced the gross bedform-normal transport rule (from now the GBNR), which can be generalized to multidirectional flows in natural environment (Ping et al., 2014). Using this rule together with the dune shape classification, a given wind regime should therefore be associated with a specific dune type and a single orientation. This unique line of reasoning has been recently challenged on the basis of experimental, numerical and field observations. Here, we review these observations and present a set of evidences that demonstrate that two dune growth mechanisms can be at work and coexist. According to sand availability and flow properties, we develop a formalism for dune pattern recognition, including qualitative and quantitative variables such as dune shape, orientation, wavelength and growth rate.

2 TWO DUNE GROWTH MECHANISMS

Comparing the dune orientations in arid desert on Earth with the alignment predicted by the GBNR, Lancaster (1991) observed a clear mismatch for linear dunes. In addition, dunes with different orientations are locally observed in many planetary environments, and asymmetric barchans clearly exhibit two crest orientations, one associated with the main crescentic body, the other associated with the alignment of the longer arm. All these observations indicate that there was a hidden controversy about dune orientation and that current models were not sufficient to explain the observed diversity of dune patterns.

Using underwater laboratory experiments, Reffet et al. (2010) showed that under symmetric bidirectional flow with a divergence angle $\theta_d > 90°$, a sand pile located on a non-erodible bed slowly transforms into a longitudinal linear dune. Its crest is aligned with the mean flow and advection directions, causing the growth of a finger-like structure at the downstream end of the crest. By numerically exploring different multidirectional flow regimes with no resultant transport on a flat sand bed (RDP=0), Zhang et al. (2012) reproduced for the first time the formation of star dunes with arms elongating in multiple direction. Overall, we demonstrated that the finger-like structures associated with star-dunes arms were in fact not aligned according to predictions of the GBNR (Fig. 2a). Instead, this specific type of dunes elongate in the direction of the sediment flux at the crest, which may significantly differ from the direction of the sand flux on a flat sand bed because of the speed-up effect (i.e., the acceleration of the flow over a positive topography). It then became clear that this essential ingredient had to be taken into account to predict dune orientation and that it was necessary to evaluate the impact of sediment availability, not only on dune shape, but also on dune growth and orientation.

On the basis of this evaluation, a new set of underwater laboratory experiments with asymmetric bidirectional flow regimes, and different conditions of sediment availability have been developed. According to the bedform dynamics observed in these experiments, Courrech du Pont et al. (2014) demonstrated that there are indeed two dune growth mechanisms and that sediment availability selects the overriding mechanism for dune formation or evolution (Fig. 2b):

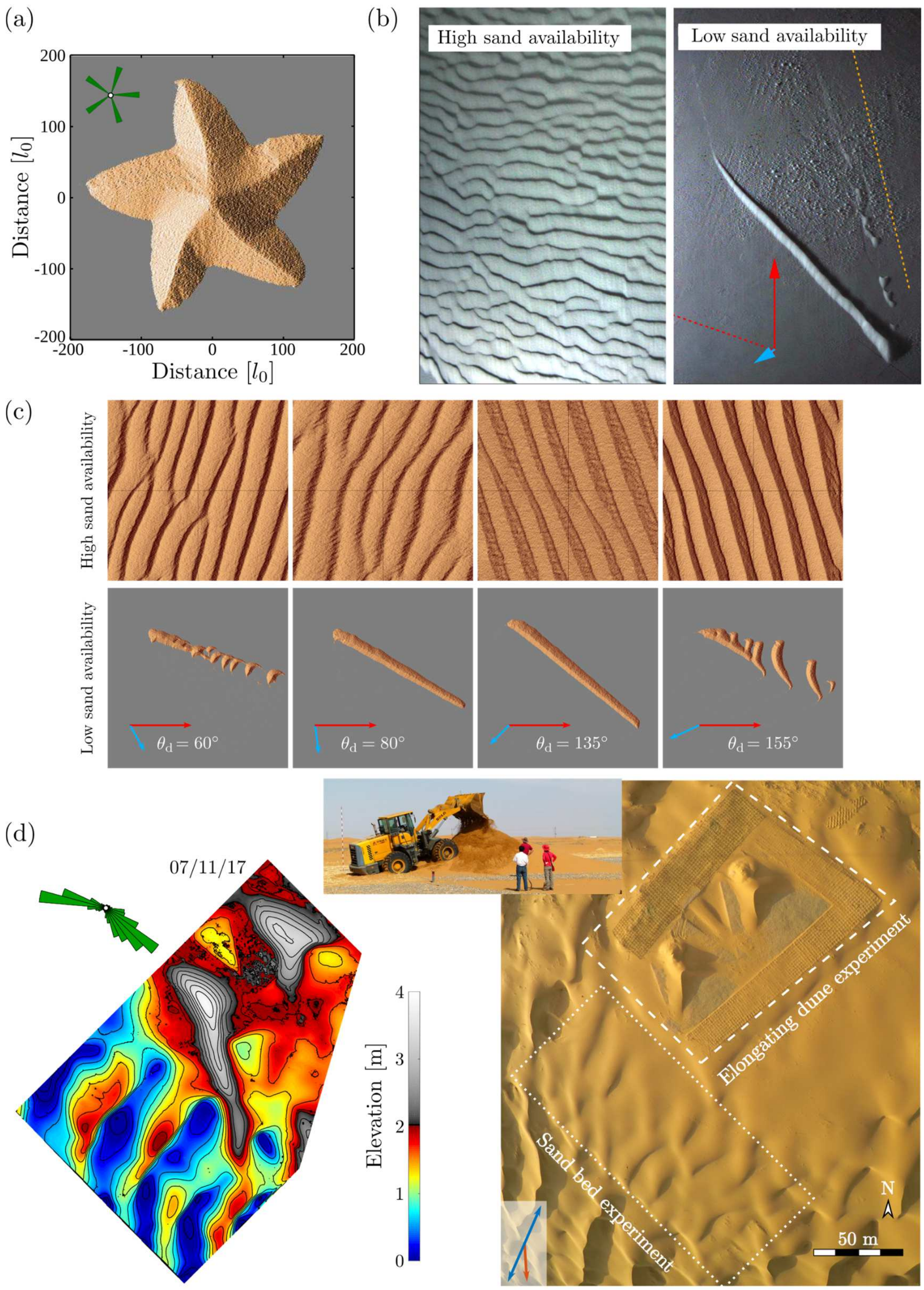

Figure 2. Two dune growth mechanisms: (a) Numerical simulations of star dunes (Zhang et al., 2012). Crest alignments switch from the bed instability to the elongating mode where sediment is no longer available. (b) Subaqueous laboratory experiments with the same wind regime (see arrows) but different condition of sediment availability (Courrech du Pont et al., 2014). Dashed and dotted lines show the bisector and the resultant sediment flux on a flat surface, respectively. (c) Same as (b) using numerical simulations (Gao et al., 2015) for different angles of divergence θ_d. (d) Landscape scale experiment showing the coexistence of the two dune growth mechanism under natural wind conditions (Lü et al., 2021; Lü et al., 2022).

1- On an erodible sand bed, dunes grow in height and migrate selecting the orientation α_I for which the normal-to-crest components of transport are maximum, a result consistent with the GBNR when considering the speed-up effect. This is the bed instability mode, which refers to the ability for a sand bed to organize in periodic bedforms as soon as there is transport

2- On a non-erodible ground, dunes grow by elongation away from the source of sediment in the direction α_F of the resultant sand flux at the crest. This is the fingering or the elongating mode. Classical geomorphological sand sources are depositional areas related to coastal or river systems, topographic obstacles or pre-existing dunes (Gadal et al., 2020b).

Hence, the same multidirectional wind regime is associated with two modes of dune orientations according to the sand availability. These two modes may locally coexist as a result of changes in sediment availability or due to the development of superimposed bedforms.

In addition to the model described below (Sec. 3), the spatial and temporal development of incipient dunes in the bed instability mode can also be theoretically analyzed through a linear stability analysis (Elbelrhiti et al., 2005; Narteau et al., 2009, Lü et al., 2021). In multidirectional flow regimes, it predicts not only dune orientation but also the selected pattern wavelength, the associated initial growth rate, and propagation velocity (Gadal et al., 2019; Gadal et al., 2020a; Lü et al., 2021). While the elongating mode of dune growth is not associated with a specific size-selection mechanism, the observed periodicity in fields of elongating dunes reflects the interdependence of dune patterns over the course of their evolution, when they develop from periodic dunes in the bed instability mode or interact through collisions or flow perturbations (Gadal et al., 2020b).

3 A MODEL FOR DUNE ORIENTATIONS

Let us consider an infinite linear dune of orientation α of height H, and width 2W. To account for the wind speed-up, the shear velocity vector $\boldsymbol{u}_{\mathbf{flat}}$ and the flow orientation θ can be used to determine the shear velocity at the crest

$$\boldsymbol{u}_{\mathbf{crest}} = \boldsymbol{u}_{\mathbf{flat}}\,(1+\beta\,(H/W)\,|\sin(\theta-\alpha)|) \quad (1)$$

where $(H/W)|\sin(\theta-\alpha)|$ is the aspect-ratio of the dune experienced by the flow and β a dimensionless coefficient that takes into account other physical ingredients (e.g., roughness) affecting surface wind speed (Jackson and Hunt, 1975). Then, a transport law adapted to the studied environment can be used to determine the flux vectors $\boldsymbol{Q}_{\mathbf{flat}}$ and $\boldsymbol{Q}_{\mathbf{crest}}$ on a flat sand bed and at the crest, respectively. The parallel- and normal-to-crest components of transport at the crest are

$$Q_{//} = ||\boldsymbol{Q}_{\mathbf{crest}}||\cos(\theta-\alpha) \qquad (2)$$
$$Q_{\perp} = ||\boldsymbol{Q}_{\mathbf{crest}}||\sin(\theta-\alpha)$$

The growth rate of dunes is taken proportional to the overall normal-transport at the crest averaged over the entire time period under consideration,

$$\sigma = \langle|Q_{\perp}|\rangle/(HW) \qquad (3)$$

According to the GBNR, but taking into account the speed-up effect, dunes in the bed instability align in the direction for which the growth rate is maximum:

$$\left(\frac{d\sigma}{d\alpha}\right)_{\alpha_I} = 0 \qquad (4)$$

Dunes in the fingering modes elongates in the direction of the sand flux at the crest, the orientation for which $\langle Q_{\perp}\rangle=0$ and $\langle Q_{//}\rangle>0$, i.e.,

$$\arccos\left(\frac{Q_{crest}(\alpha_F)\cdot u_{\alpha_F}}{||Q_{crest}(\alpha_F)||}\right) = 1 \qquad (5)$$

where $u_{\alpha F}$ is the unit vector in the direction α_F. The orientations $\{\alpha_I, \alpha_F\}$ of the dunes in the bed instability and the elongating modes being determined, all the parameters characterizing their dynamics can be estimated. For example, Eqs. 2 and 3 give the sand flux vectors at their crest $\{\boldsymbol{Q}_I, \boldsymbol{Q}_F\}=\{\boldsymbol{Q}_{crest}(\alpha_I), \boldsymbol{Q}_{crest}(\alpha_F)\}$ and their growth rate $\{\sigma_I, \sigma_F\}=\{\sigma(\alpha_I), \sigma(\alpha_F)\}$, respectively. The growth-rate ratio σ_F/σ_I can be used to estimate the predominant mode of dune orientation in zones of low sand availability.

4 VALIDATIONS AND APPLICATIONS

4.1 Validation of the elongation mechanism

Using the wind data of climate reanalyses over the past 30 yr, Courrech du Pont et al. (2014) verified that the predicted orientations $\{\alpha_I, \alpha_F\}$ agree within 5° with the alignment of aeolian dune patterns in terrestrial sand seas, not only for small dunes (~30 m wide) but also for larger and older dunes (~1 km wide). Interestingly, most of the linear dune patterns are oriented according to the elongating mode of dune growth, suggesting that most of them develop along aeolian transport routes from source areas (Chanteloube et al. 2022).

Gao et al. (2015) numerically investigated the development of bedforms for two different conditions of sand availability to provide evidence for the expression of the two dune growth mechanisms across the entire parameter space of bidirectional flow regimes (i.e., divergence angle, transport ratio). The complete phase diagrams of dune shape and orientation in both the bed instability and the elongating modes are used to quantitatively validate the prediction of the model (see Sec. 3). In the simulations, different dune patterns emerge in zones of low sand availability (Fig. 2c), and there are systematic transitions from trains of barchans to isolated linear elongating dunes. These transitions are well captured by the growth-rate ratio σ_F/σ_I, which compares the ability of the flow to build the dune topography in the two modes of dune growth.

Based on 50 yr of aerial and satellite imagery of aeolian landforms in Niger, Lucas et al. (2015) demonstrate for the first time in the field that dunes can elongate in the direction of the resultant sand flux at the crest, with no lateral migration. As they develop downwind of residual hills in a zone of low sediment availability submitted to bimodal wind regime, these longitudinal dunes are ideal bedforms to isolate and quantify the elongation mechanism. From the elongation rate of individual dunes, we then derived the sand flux parallel to the crests to show that this specific dune type can also be studied for assessing transport and wind conditions, comparably to the more traditional methods using the migration of transverse and barchan dunes in the bed instability mode.

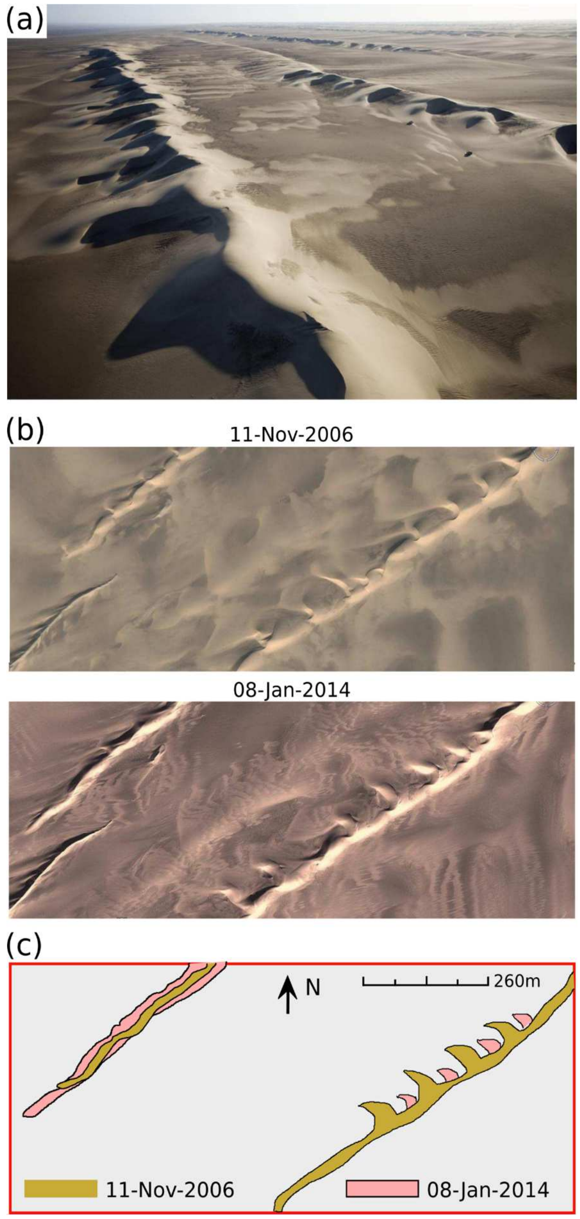

Figure 3. (a) Raked linear dunes in the Kumtagh desert in China. (b) Evolution of dune shape from 2006 to 2014 showing (c) elongation of the linear pattern and the oblique migration of the superimposed dune pattern in the bed instability mode of dune growth.

4.2 Coexistence of the two growth mechanisms

A landscape-scale experiment at the edge of the Gobi desert is a unique site to study dune morphodynamics under natural wind conditions and controlled boundary conditions (Ping et al., 2014). After flattening a dune field in 2013, and based on 4 yr of high-resolution topographic data, Lü et al. (2022) showed how, depending on sand availability, the same wind regime can lead to two different dune orientations, which reflect the two dune growth mechanisms (Fig. 2d). As periodic oblique dunes emerge from a sand bed and develop to 2 meters in height, we analysed the initial linear phase of the bed instability (Lü et al., 2021) and then the defect dynamics that drive the non-linear phase of pattern coarsening. Starting from conical sand heaps deposited on gravels, we observed the transition from dome to barchan and asymmetric barchan shapes (Lü et al., 2022). We identified a minimum size for arm elongation and evaluate the contribution of wind reversals to its longitudinal alignment. These experimental field observations support the model and the numerical simulations (Gao et al., 2015; Rozier et al., 2019), providing practical solutions for quantitative analysis of dune evolution under various wind regimes and bed conditions.

Raked linear dunes keep a constant orientation for considerable distances with a marked asymmetry between a periodic pattern of semi-crescentic structures on one side and a continuous slope on the other (Fig. 3). Lü et al. (2017) showed that this shape is associated with a steady-state dune type arising from the coexistence of the two dune growth mechanisms. Primary ridges elongate in the direction of the resultant sand flux. Semi-crescentic structures result from the development of superimposed dunes growing in the bed instability mode. In the particular case of raked linear dunes, these two mechanisms produces primary and secondary ridges with similar height but with different orientations, which are oblique to each other. The raked pattern develops preferentially on the leeward side of the primary ridges according to the direction of propagation of the superimposed bedforms. As shown by numerical modelling, raked linear dunes occur where both these oblique orientations and dynamics are met.

4.3 Planetary dunes and the inverse problem

On Titan, a moon of Saturn, dune fields cover more than 17% of the surface. Their confinement to the equatorial belt, shape, and eastward direction of propagation offer crucial information regarding both the wind regime and sediment supply. Lucas et al. (2014) presented a comprehensive analysis of Titan's dune orientations using automated detection techniques on radar images. By investigating the two dune growth mechanisms using wind fields generated by climate modelling, we found that the giant dunes on Titan grow by elongation on a non-mobile substratum. To be fully consistent with both the local crestline orientations and the eastward propagation of Titan's dunes, the sediment should be predominantly transported by strong eastward winds, most likely generated by equinoctial storms or occasional fast westerly gusts (Charnay et al., 2015; Rodriguez et al., 2018). Additionally, the meridional transport predicted in models can explain why Titan's dunes are confined within ±30° latitudes, where sediment fluxes converge.

Dunes on Mars also show clear evidence of the coexistence of the two dune growth mechanisms. Using the high contrast between the dune material and substrate, Fernandez-Cascales et al. (2018) provided the first quantification of relationship between sediment availability and dune orientation. Abrupt and smooth dune reorientations are associated with inward and outward dynamics of dunes approaching and ejecting from major sedimentary bodies, respectively. These reorientation patterns along sediment transport pathways are interpreted as discontinuous and continuous transitions from the elongating to the bed instability modes of dune growth and vice-versa. In addition, assuming bidirectional wind regimes, the intersections between model predictions for the two modes permitted solving of the inverse problem of predicting the wind regime from dune orientation. The relationships between sediment cover and dune orientation can therefore be used to constrain the flow regime in environments where direct measurements are impossible.

5. CONCLUSION

The two dune growth mechanisms have now been observed in many planetary environments and documented in the field through a dedicated set of landscape-scale experiments. For both mechanisms and their interactions, the results of various laboratory experiments and a large number of numerical simulations support comprehensive theoretical models, boosting confidence in their applicability for quantitative predictions of dune morphodynamics (shape, orientation, growth and migration rates) under various flow regimes and bed conditions.

Opposite flow directions are ubiquitous over subaqueous bedforms in tidal environments. In addition, there are many possible sources of tidal asymmetry and the complexity of specific bathymetry and geometry in estuaries can produce multidirectional flow regimes. Hence, the dune growth mechanisms discussed here may also coexist in river and oceanic settings. In this case, marine and river dunes may offer new opportunities for better characterization of the flow regimes, sediment resources and transport properties.

6 REFERENCES

Magnolia, R.A., 1941, The physics of wind blown sand and desert dunes, Methuen.

Chanteloube C., Barrier, L., Derakshani, R., Gadal, C., Braucher, R., Payet, V., Léanni, L., Narteau, C., 2022, Source-to-sink aeolian fluxes from arid landscape dynamics in the Lut Desert, Geophysical Research Letters, 49, e2020GL097342, 2022.

Charnay B., Barth, E., Rafkin, S., Narteau C. et al., 2015, Methane storms as a driver of Titan’s dune orientation, Nature Geoscience, 8, 362-366.

Courrech du Pont S., C. Narteau, X. Gao, 2014, Two modes for dune orientation, Geology, 42, 743-746.

Elbelrhiti, H., Claudin, P., Andreotti B., 2005, Field evidence for surface-wave-induced instability of sand dunes. Nature 437, 720–723.

Fernandez-Cascales L., Lucas, A., Rodriguez, S., Gao, X., Spiga, A., Narteau, C., 2018, First quanti-fication of relationship between dune orientation and sediment availability, Olympia Undae, Mars, Earth and Planetary Science Letters, 489, 241-250.

Gadal, C., Narteau, C, Courrech du Pont, S., Rozier, O., Claudin, P., 2019, Incipient bedforms in a bidirectional wind regime, J. Fluid Mech., 862, 490–516.

Gadal C., C. Narteau, S. Courrech du Pont, O. Rozier, P. Claudin, 2020a, Spatial and Temporal Development of Incipient Dunes, Geophysical Research Letters, 47, e2020GL088919.

Gadal C., C. Narteau, S. Courrech du Pont, O. Rozier, P. Claudin, 2020b, Periodicity in fields of elongating dunes, Geology, 48.

Gao X., C. Narteau, O. Rozier, S. Courrech du Pont, 2015, Phase diagrams of dune shape and orientation depending on sand availability, Scientific Reports, 5, 14677.

Gao X., Narteau, C., Gadal, C., Migration of reversing dunes against the sand flow path as a singular expres-sion of the speed-up effect, Journal of Geophysical Research, 126, doi:10.1029/2021JF006492.

Hunter, R. E., Richmond, B. M., Alpha, T. R., 1983, Storm-controlled oblique dunes of the Oregon coast. Geol. Soc. Am. Bull. 94, 1450–1465.

Jackson, P. & Hunt, J., 1975, Turbulent wind flow over a low hill. Q. J. Roy. Meteorol. Soc. 101, 929–955.

Lancaster N., 1991, The orientation of dunes with re-spect to sand-transporting winds: a test of Rubin and Hunter’s gross bedform-normal rule, NATO advanced workshop on sand dust, and soil and their relation to aeolian and littoral processes, University of Aarhus, 47-49.

Lü P., C. Narteau, Z. Dong, O. Rozier, S. Courrech du Pont, Unravelling raked linear dunes to explain the coexistence of bedforms in complex dunefields, Nature Communications, 8, 14239, 2017.

Lü, P., Narteau, C., Dong, Z., Claudin, P., Rodriguez, S., An, Z., Fernandez-Cascales, L., Gadal, C., Courrech du Pont, S., 2021, Direct validation of the dune instability theory, Proceedings of the National Academy of Sciences, 18, e2024105118.

Lü, P., Narteau, C. , Dong, Z., Claudin, P., Rodriguez, S., An, Z., Gadal, C., Courrech du Pont, S., 2022, Coexistence of two dune growth mechanisms in a landscape-scale experiment, Geophysical Research Letters, 49, e2021GL097636.

Lucas A., Rodriguez, S., Narteau, C., Charnay, B., Courrech du Pont, S., 2014, Growth mechanisms and dune orientation on Titan, Geophysical Research Letters, 41, 6093-6100.

Lucas A., C. Narteau, S. Rodriguez, O. Rozier, Y, Callot, A. Garcia, S. Courrech du Pont, 2015, Sediment flux from the morphodynamics of elongating linear dunes, Geology, 43, 1027-1030.

Narteau, C., Zhang, D., Rozier, O., Claudin, P., 2009, Setting the length and time scales of a cellular automaton dune model from the analysis of superimposed bed forms, J. Geophys. Res. Earth Surf, 114, 1–18.

Ping, L., Narteau, C., Dong, Z., Zhang, Z., Courrech du Pont, S., 2014, Emergence of oblique dunes in a landscape-scale experiment, Nat. Geosci., 7, 99–103.

Reffet, E., Courrech du Pont, S., Hersen, P., Douady, S., 2010, Formation and stability of transverse and longitudinal sand dunes, Geology, 38, 491–494.

Rodriguez S. et al., 2014, Global mapping and characterization of Titan's dune fields with Cassini: Correlation between RADAR and VIMS observations, Icarus, 230, 168-179.

Rodriguez S. et al., 2018, Gobservational evidence for active dust storms on Titan at equinox, Nature Geosci., 11, doi:10.1038/s41561-018-0233-2.

Rozier O., Narteau, C., Gadal, C., Claudin, P., Courrech du Pont, S., 2019, Elongation and stability of a linear dune, Geophysical Research Letters, 46, 14521-14530.

Wasson, R. & Hyde, R., 1983, Factors determining desert dune types. Nature, 304, 337–339.