Flow effect on the morphology and dynamics of barchan dunes

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Abstract

Barchans are well-known Aeolian crescent-shaped dunes that form under a directional wind on a firm ground. Although their morphology is now well described, the link between airflow and barchan dynamics is still poorly understood. This lack of knowledge comes from the natural difficulty to investigate on the field. However, its crescentic morphology can also develop under water on a much smaller scale, which allows easier studies. Here by creating experimentally solitary sub-aqueous barchans in the lab, we explore the dynamical behavior of crescent-shaped sedimentary structures. First results show a strong influence of the flow properties on both the shape and the motion of the dune.

1. Similarity between air and sub-aqueous dunes.

1.1 Aeolian sand dunes: basics

The harshness of conditions in desert, as well as the difficulty to achieve precise measurements on such large structures makes fieldwork uneasy. For example, Star dunes can reach up to several hundred meters high, with tortuous arms extending from the summit on several kilometers. The most studied mobile dune, the barchan (see Fig. 1), is far less large (Bagnold, 1941). Its width and length are typically between 15 and 300 meters, while its height, ranges from 1 meter to 30 meters (Cooke et al., 1993). However, this scale of size remains too large to achieve easily morphological measurements on the field. Another important problem is the timescale involved: barchans are highly mobile dunes compared to other sediment pattern motions, typically of 40 meters a year, but still very slow compared to a regular mission duration.

Fig. 1 – Barchan dunes shape. (a) An Aeolian barchan dunes in the region of Tarfaya, South Morocco. Its length is approximately 30 meters. (b) A Sub-aqueous barchan dune created in the lab from a 5 cm-wide conical sand-pile. Both structures present the same morphological features: both shapes have a flat aspect ratio, with a recirculation-bubble in the lee of slip-faces and with two horns pointing downwind.

These technical problems are intensified by the lack of control on wind and meteorology conditions. Hence it is quite impossible to capture dynamical processes on the field. Then, laboratory experiments are highly required to study barchans dynamics properly and, more generally, Aeolian patterns development. However, barchans dunes have a minimal size of typically 10 meters wide, indicating that no experiment can reproduce barchan on the laboratory scale in the air (Bagnold, 1941; Andreotti et al., 2002). That size limit can be explained by the existence of a characteristic length of adaptation for the sand flux: L_{sat} (Kroy et al., 2002; Hersen et al., 2002). As a matter of fact, the sand flux reacts to the form of the dune through deposition/erosion processes. Those cannot occur immediately, but rather on L_{sat}. A dimensional analysis shows that L_{sat} scales with the ratio of the grains density and the fluid density (Andreotti et al., 2002). It indicates that, under water, it should be possible to produce about 1000 times smaller barchans with the same morphological behavior. In fact, this rescaling could also have been guessed by the existence of crescent-shaped bed-forms in natural conditions, such as river or marine environment.

1.2 Experimental Set-up

Given the previous remarks, a simple device (Hersen et al., 2002) can be used to create barchan dunes in laboratory on a centimeter scale (see Fig. 1). A sand pile is dropped on a plate in a water tank, and then, this plate is put into motion by an external motor (see Fig. 2). In the frame of the plate, the motion is equivalent to a water flow shaping the sand-pile. In order to reproduce a unidirectional wind, the plate motion is not symmetric: it moves fast in one direction, leading to the erosion of the sand-pile, and it slowly comes back to its starting point, to ensure that no grains could move throughout this return-phase. This motion is then repeated several times. After a few periods (depending on the precise parameters use for the plate movement) the conical sand-pile takes a crescent shape and moves on (see Fig.1). This apparatus is thus an alternative way to investigate the dynamics of barchan dunes, and more generally sub-aqueous sedimentary structures formed under a directional flow.

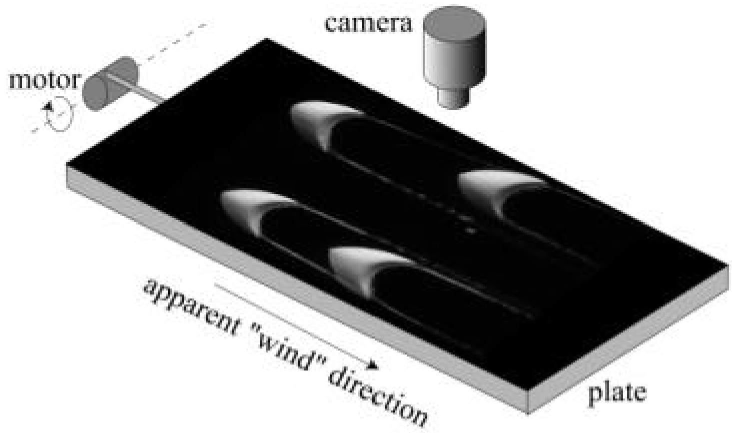

Fig. 2 – Experimental set-up. The plate dimensions are 40x30 cm, and the amplitude of the motion is 50 cm. The sand-pile shape is monitored with the help of a CCD video camera moving with the plate. The photograph shows four aquatic barchans on the plate created with this experiment (approximately 5 cm wide). This shows its ability to easily produce one or several barchan dunes. Notice that the sand leak through the horns is clearly visible.

2. Influence of the wind properties

2.1 Plate movement and control parameters

The plate movement is divided into four basic steps: a constant acceleration, during t_a; a constant speed movement, during t_b; a deceleration, during t_c; a stop phase of one second; and finally a very slow movement backward. This last phase is slow (2 cm/s) to ensure that no grain can move. Moreover, these three parameters (t_a, t_b and t_c) are linked because the amplitude of the plate motion, Le, is fixed to 50 cm for technical reasons. A compromise must be found between a relatively fast motion, in order to reach the motion threshold for the grains and the necessity to decelerate as slowly as possible to prevent a counter flow from developing and disturbing the dune shape. For that reason, we impose t_c = 1s. Afterwards, the value of t_a and t_b condition the resulting water flow. These parameters do not have the same status: t_a controls the unsteady effect (acceleration) while t_b controls the constant speed evolution. In fact, changing these parameters is strictly equivalent to change γ and v, the initial acceleration and the final velocity of the plate. The flow produced is sufficient to move the grains and to get a barchan shape from a conical sand-pile. Assuming that the flow properties follow the motion of the plate, at least in first approximation, the experimental setup is then a way to deal with several issues on the relation between flow properties and barchan dynamics. The first one is to try to characterize the link between the mobility of barchan and the flow properties. Then, we can wonder if the shape remains the same whatever γ and v.

2.2 Influence of γ and v

To study the influence of γ and v, two types of experiments have been conducted. For the first-one, γ is kept constant at 1.8 $m.s^{-2}$, while v varies from 16.8 $cm.s^{-1}$ to almost 30 $cm.s^{-1}$. For the second one, the final speed of the plate is always 28 $cm.s^{-1}$, while the acceleration time t_a, varies from 70 ms to 600 ms. Each experiment starts with the same conical sand-pile (approximately 4 cm wide). The evolutions of the center of mass of the produced barchans are plotted on Fig. 3 and Fig. 4.

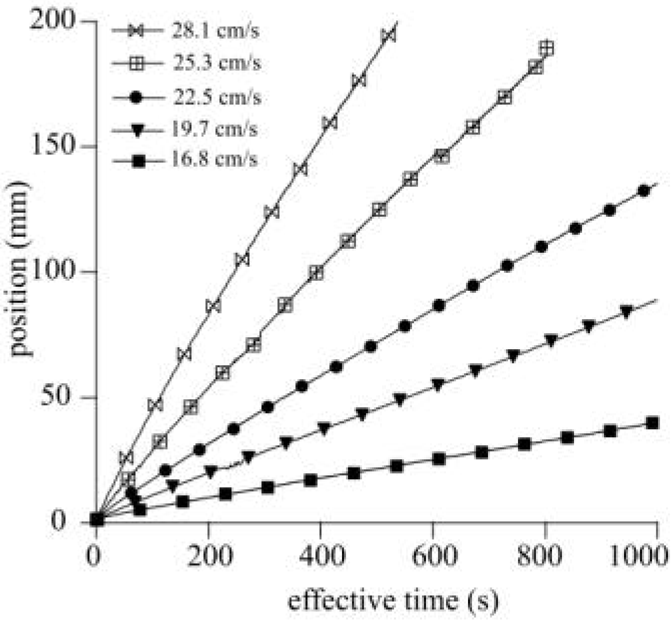

Fig 3 – Influence of v. The barchan center of mass position is plotted versus the effective time of the motion, that is to say the time during which the plate moves. Increasing the plate final speed, leads to faster barchan dunes.

The first observation is that increasing v increases the barchan velocity. A trivial analysis indicates that, for the same shape, the speed of dune is faster for a stronger wind flow. This is in keeping with our result: a stronger speed flow increases the sediment transportation rate, and accordingly, the dune speed increases. More precisely, for the extreme value of v, the dune speeds are 0.2 cm/mn and 2.15 cm/mn. It would be interesting to determine the scaling between the final speed of the plate and the corresponding dune speed. However, this direct rescaling is not easy since acceleration of the plate has also an influence on barchans dynamics.

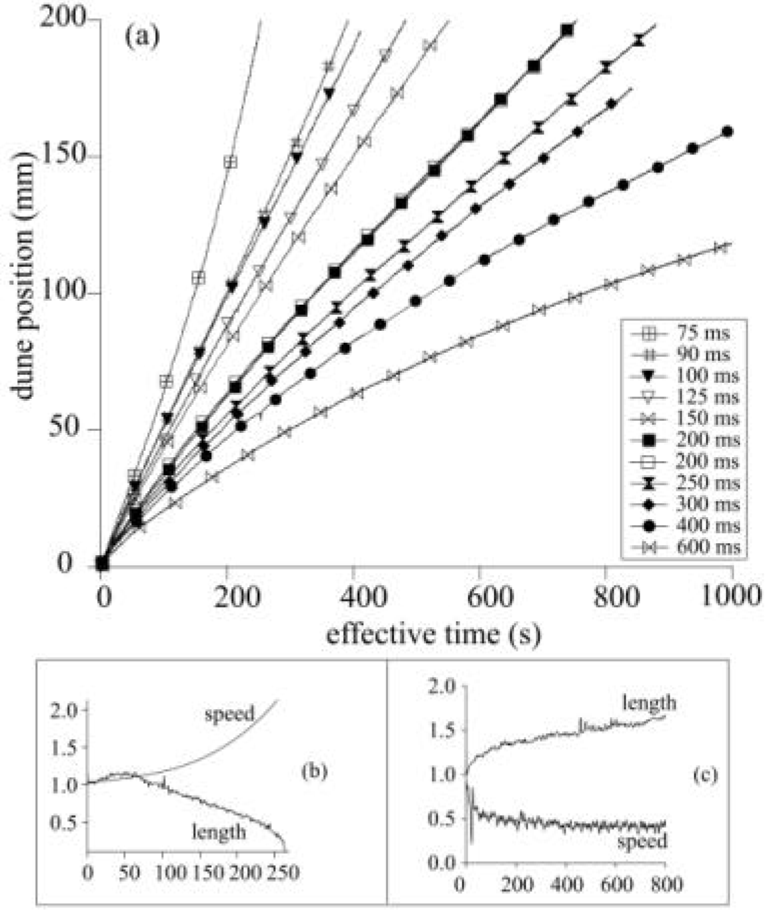

Fig 4 Influence of γ. (a) Evolution of the position of the dune for different accelerations while the final speed is always equal to 28 cm/s. Then the larger t_a is the smaller γ is. (b) Evolution of the normalized speed and the normalized length for the fastest accelerating dune, t_a = 70 ms. Notice that the speed data plotted here results from a fitting analysis. (c) Same plot for the more decelerating dune, t_a = 600 ms.

On the same basis, Fig. 4 shows that γ has a tremendous effect on the barchan speed: increasing the acceleration of the plate naturally leads to improve the basal shear stress. Then the dune moves faster. More precisely the maximal and minimal dunes speed are approximately 0.6 cm/mn and 5 cm/mn. However, for low or high plate acceleration, the speed of the dune evolves with time, indicating the complex role played by γ. The increase in speed prompted by plate high accelerations can be easily understood: as the dune shrinks (see inset (b) on Fig. 4), it also has to accelerate with time as proposed by classic theory (Bagnold, 1941). However, the cases where dunes decelerate are a bit stranger. In fact, the dune has also to shrink since there is an output sand leak from the horns and no influx, but nevertheless it decelerates. Therefore, this should come from the progressive change of the barchan shape. As a matter of fact, since the initial erosion is not strong, the summit is much more eroded than the rest of the barchan, and the barchan elongates (see inset (c) on Fig.4). The new shape, now flatter, leads to smaller erosion, which reduces the dune speed. This supports the theory of Kroy et al., (Kroy et al., 2002) who claim that the speed of dune should depend on the length of dunes rather than of their height. The latter argument comes from the fact that the sand flux at the crest depends on the speed-up at the crest. In particular it has a functional dependency with the aspect ratio of the dune, then the speed of a steady dune writes:

$$c = \frac{q}{h} \propto \frac{h}{L}\frac{1}{h} \propto \frac{1}{L} \qquad (1)$$

Hence, it appears that the flow acceleration can strongly modify the erosion rate, and the dynamical behavior, and shape of sediment pattern as well. Fig. 5 shows the different shapes obtained from the same conical sand-pile after it moves to the same position on the plate for extreme values of the parameters v and γ. The dune is always crescentic whatever the plate motion, and this result suggests that the crescent shape of barchan can be in fact considered as an attractor shape (Werner, 1989): even if the precise shape can vary a lot, the general morphology remains. Moreover, Fig. 5 shows that a change in the speed of the plate only does not affect the shape strongly. On the contrary, shapes are affected by a change in γ. Furthermore, as the variation of the size evidences the change of the output sand flux with the flow conditions, Fig 5. indicates also the output sand flux evolution with γ and v. It appears that a variation in the speed of the plate leads to variation of the output flux. As a matter of fact, by definition, dunes shapes represented on Fig.5 had not been submitted to erosion during the same time. It seems that changing v does not change the mass balance, indicating that the erosion power and the output sand flux are both related to the motion of the plate in the same way. However, changing γ can lead to huge change since for the larger acceleration, t_a = 70 ms, the dune disappears before leaving the plate. It may come from the strong vortices produced in the lee of the dune. While developing, they can extract grains from the dune by the side. This is supported by the fact that sand is more visible in the lee of horns for strong acceleration of the plate. This means that changing γ is a way to change the importance of the output flux. More precisely, the fastest dunes in Fig 3 and Fig 4 have a comparable speed, but not the same output flux at all. Finally, thanks to these preliminary experiments, it appears that the flow properties are crucial to understand the shape evolution, and also the rate of sediment transportation, under water, and forcibly in the air. In particular, the acceleration of the plate induces drastic effects on the behavior of the solitary barchan shape.

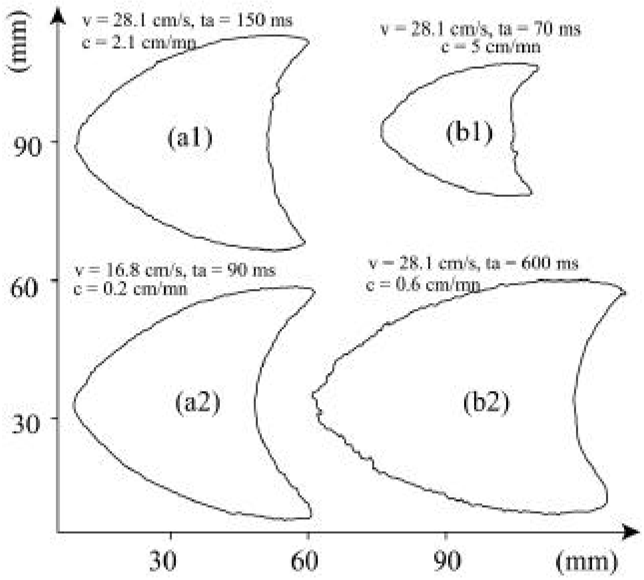

Fig. 5 – Influence of v and γ on the barchan shape. The shapes of four dunes created with extreme values of v and g, once they reach the same position on the plate, are shown. (a1) for maximal v, (a2) for minimal v, (b1) for maximal g and (b2) for minimal g. It can be seen that the acceleration has a strong influence on the erosion. On the contrary, the shapes differences for different speed of the plate appears to be far less important.

2.3 Influence of wind direction

The proposed experiment can also be used to explore more complex effects like a change in the wind direction. This kind of approach is motivated by field observations of wind, which often changes its direction for a short period of time. Then, as velocity fluctuations, this could also affect their stability, shapes and propagation. As in the previous section, starting from a conical sand-pile, a sub-aqueous barchan forms and propagates on the plate. When the barchan reaches the center part of the plate, the plate is stopped, and the dune is rotated of the angle θ. When the motion starts again, the barchan mutates in order to adapt to new wind configuration. Fig. 6 shows two different experiments made with $\theta = 90°$ and $\theta = 180°$. From those experiments, we can conclude that the barchan dune adapts quickly to a change in wind condition: after typically 20 oscillations the barchan shape is recovered. In other words, the major part of the adaptation is finished, before the dune moves further than its length. A striking effect of wind direction variation is the modification of the output sand flux: in both experiments, some sand escapes from the main body. In particular, the dune adaptation leads for certain value of θ to the apparition of small barchans, which separate from the main barchan structure, and propagate faster downwind. Finally, Those conclusions shed light on the role of another important part of the flow: the recirculation bubble in the lee of the dune. The dune re-adaptation is not only produced naturally by erosion on its upwind side, but also by the recirculation bubble development on the sheltered side. This shows the importance of eddies and vortex structures on the whole dynamics of sub-aqueous bed-forms. Moreover, from those very basic observations, we can assume that changing wind in reality will lead not only to large shaping effect but also to effect on stability effect. As a matter of fact, a barchan is stable only if the output flux is compensated by an equivalent influx. However, turning the wind lead to increasing the output flux by emission of several small barchans. Hence, fluctuation of wind direction can, as well as wind speed fluctuations leads to a drastic change of the overall mass balance for a dune. Strikingly, once again, the barchan dune readapts to its new wind direction environment, supporting the attractor quality of this morphology. As a matter of fact, we could imagine that changing so radically the wind direction would completely destroy the shape.

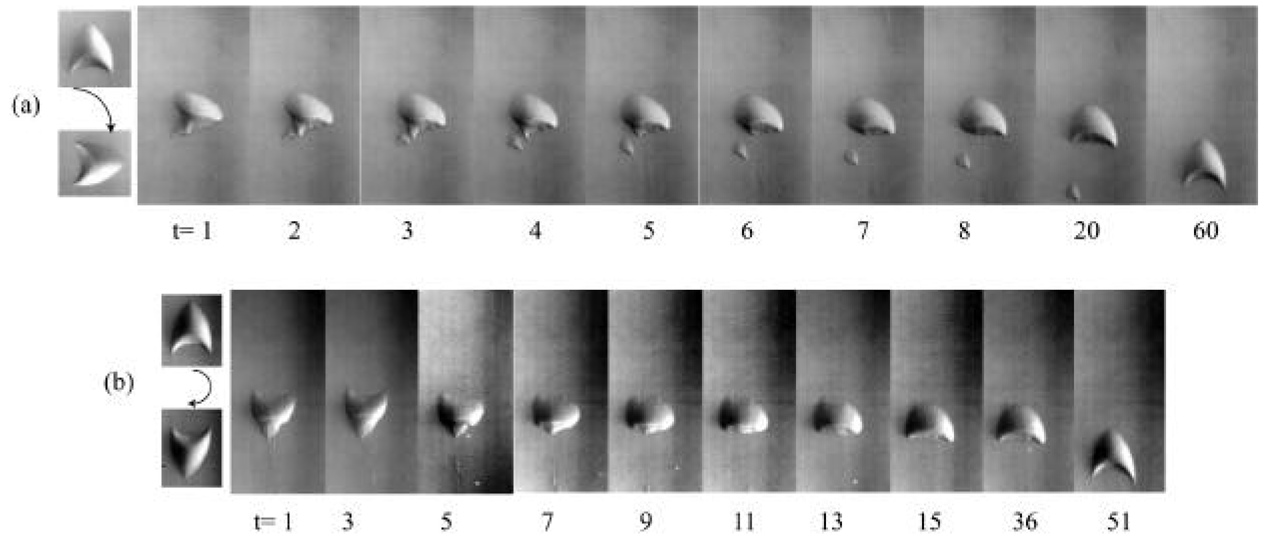

Fig. 6 – (a) Barchan evolution after a rotation of $\theta = 90°$. The barchan dune (5 cm wide) recovers its initial orientation after a few periods. The dune needs to reshape its surface completely and this leads to the destruction of the downwind horns, which separates from the dune and forms a tiny and fast sub-aqueous barchan. (b) Barchan evolution after a rotation of $\theta = 180°$. Again, the barchan adaptation takes only a few oscillations of the plate. However, the morphological evolution is completely different, since the barchan literally moves the other way round, its horns moving from the upwind side to the downwind side.

3. Towards dune interactions

In short, we have shown that the shape of barchan dune, under water, is strongly dependent on the nature of the flow. In particular, non-steady flow, or non-directional flow can largely disturb the classic shape of barchan dunes and its dynamics. These remarks should also apply to all sediment patterns forming under water. In particular it has been shown that the output flux of a barchan dune can strongly vary according to wind properties. This is a very important issue, since barchan dune stability on the field is not completely understood (Hersen et al., 2004). Future investigations will focus on the precise survey of the response of barchan structure to a change in its environment. In fact, considering barchans as the fundamental element of dunes structure blown by directional flow can lead to a better understanding of barchans corridor or barchanoïd range. As a matter of fact, the crescent aspect of river bed-forms may be seen as the superposition of many barchan structures evolving and interacting with one another under an effective flow. This way of thinking requires however to know in details the behavior of barchan dunes. This is why, understanding the solitary structure of barchan dune and its relation with the surrounding flow, is a way to approach other critical problems, such as the evolution of a natural complex pattern, including interactions between barchans. For example, we can study the basic case of a dune-dune collision. As shown on Fig. 7, collision does not appear to be a simple coalescence process, or a simple soliton-like interaction (Schwämmle et al., 2003). Rather, it appears to be an absorption/emission process, where the small dune stays in the big one, while the latter emits one or several small barchans because of the flow perturbation. This completely unknown issue can motivate future study on barchan dunes.

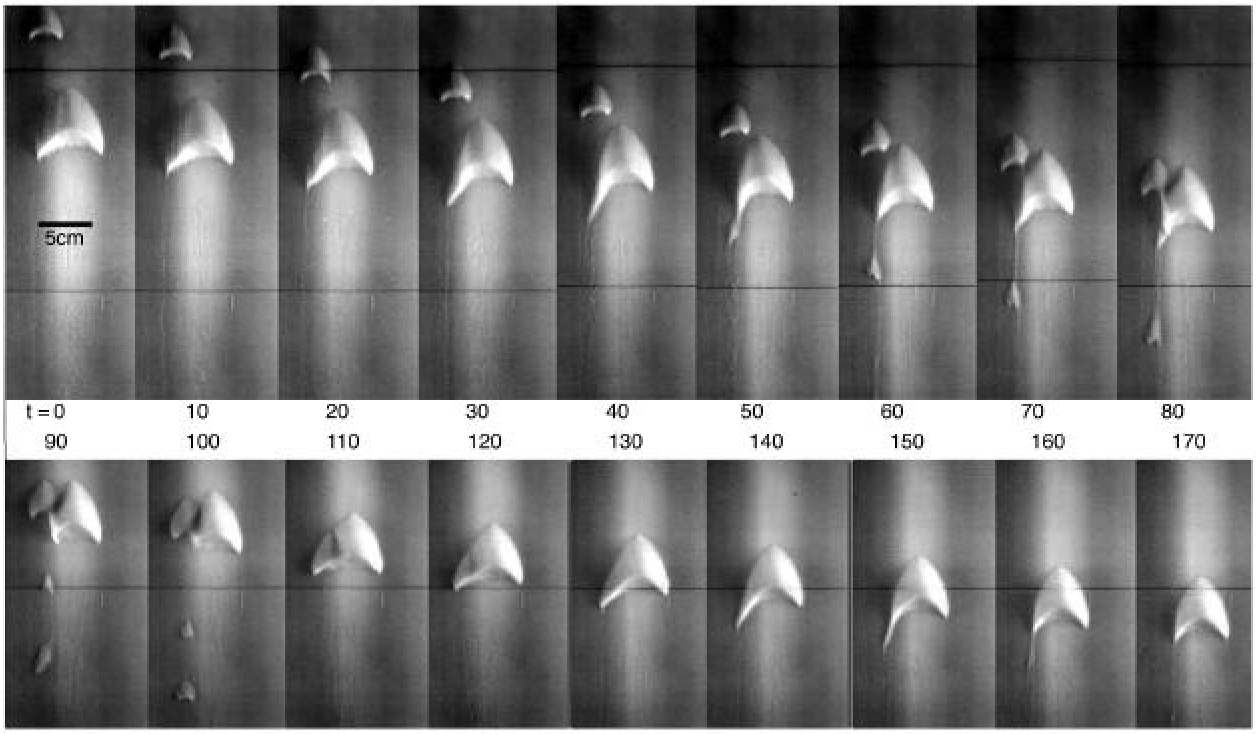

Fig 7 . Study of a dunes collision. The small one is fast enough to enter in collision with the bigger one. This leads to a complex mixing and emission process, where, in the end, a small barchan separates, while the big one readapts to a crescentic shape. There are 10 periods of the plate motion between each picture.

Acknowledgment

The author is grateful to S. Douady and F. Malloggi for encouragements and discussions about the present work and to Tomas Bohr for discussion about unsteady vortex interactions with dune shape. Nothing could have been achieved without the technical support of L. Quartier. An ACI J.Ch supported this work.

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