Research helps in understanding the dynamics of dune formation

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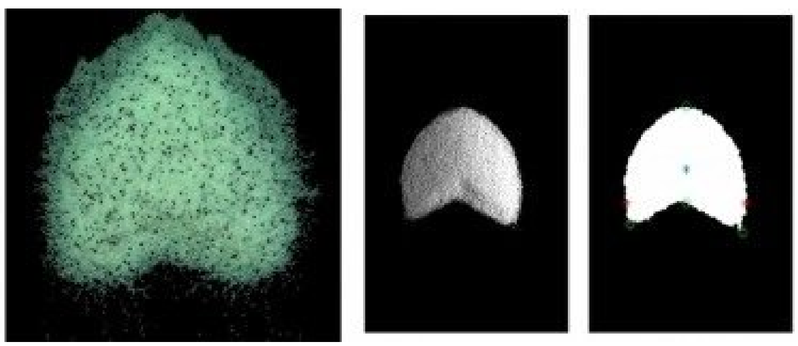

Studies of crescent-shaped dunes by Brazilian researchers could have applications in crude oil pumping and missions to Mars, among others. New findings have been published in *Physical Review Letters*. Credit: Erick de Moraes Franklin

Crescent-shaped dunes called barchans are structures that appear in a wide variety of environments, including beaches and deserts, riverbeds and the seafloor, inside water pipes and oil pipelines, and on the surface of Mars and other sandy planets with an atmosphere.

Despite differences in scale varying from 10-centimeter ripples for underwater dunes to kilometer-high mountains for Martian dunes, the dynamics of barchan formation and motion appear to be highly similar everywhere.

Research conducted at the University of Campinas (UNICAMP) in

Brazil with the support of São Paulo Research Foundation—FAPESP clarifies the dynamics of aquatic dunes. The results can also contribute to a better understanding of the topography of Mars and hence increase the probability of success in Mars missions or to the optimization and cost-effectiveness of oil flows.

"Barchans are crescent-shaped dunes that result from interaction between granular matter, typically sand, and the flow of a fluid such as gas or liquid under predominantly unidirectional flow conditions. The two horns of the crescent face in the direction of the fluid flow," said Erick de Moraes Franklin, one of the authors of the research. The study has just been published in *Physical Review Letters*.

Their findings contradict the explanation preferred for the origin and motion of these structures, at least in the case of subaqueous (underwater) dunes. "Our research shows that the emergence of barchan horns can't be explained by the conventional model, according to which the sand moves mainly in a longitudinal direction and any lateral motion of the grains is due to a mechanism similar to diffusion. The local velocity of displacement of the initial structure is supposed to be inversely proportional to its local height so that the lowest parts at the sides of the sand pile move fastest and form horns. That's not what we observed experimentally," Franklin said.

What he and Alvarez observed in a liquid medium was that the grains moved by rolling and sliding in circular paths. "The horns are formed mainly by grains that migrate from upstream regions to the region of the horns. The growth of a subaqueous barchan has a significant transverse component, which doesn't have diffusive characteristics," Franklin said.

All barchans have the same proportions in terms of the ratio of length to height and follow the same laws of motion, regardless of origin or scale. Their height is always a tenth of their length, for example. As a result, the study conducted in UNICAMP's laboratory with dunes formed at ultrafast speeds can help in understanding the dynamics of Martian terrain, such as how the Red Planet's giant dunes evolved and what they will look like thousands of years from now.

According to Franklin, the formation and motion of an underwater barchan result from the complementary or contradictory interplay of three factors: fluid flow, gravity, and grain inertia. Dunes grow as fluid flow moves grains from lower to higher regions.

Gravity acts in the opposite direction, pulling grains down and tending to make the dune flatter. Grain inertia, or more accurately, the inertial difference between the grains and the fluid, determines how the grains interact with the fluid. If grain inertia is much greater than fluid inertia, grain movement is slower than fluid movement. Instead of settling at the cusp of the dune, the grains are deposited in a lower downstream region.

"The complication is that the fluid is a continuous medium whose motion can be described by known differential equations, and physicists know how to resolve them, whereas grains make up a discontinuous medium. A dune contains billions of grains. The scale is precisely this, on the order of a billion. In addition, the grains are all different from each other," Franklin explained.

"So far, it's been impossible to describe the motion of all grains with a single differential equation. We can describe them grain by grain, but how can we integrate them all at the end? As a result, several questions about the dynamics of dunes remain open. One of these questions is why a pile of grains, whatever its shape, evolves to form a barchan, a crescent-shaped dune. In other words, why the two horns?"

Dynamics of formation

Among the various types of dunes, a barchan is known to form when the motion of a fluid (the wind over the desert or the water flow in a river, for example, occurs on average in a single direction of flow. There may be occasional variations, but in statistical terms, only one direction of flow prevails. Seen from above, this type of dune resembles a letter C. This shape means the fluid is moving from the convex side toward the horns, the twin tips of the C.

The novelty in the findings from this study is related to the dynamics of horn formation. The old model assumed that each grain moved ballistically, like a projectile describing a parabola in the vertical plane, and in the same direction as the fluid. In unidirectional motion, the lower parts move faster since their velocity is inversely proportional to local height. Hence, the two horns form. The researchers' experiment at UNICAMP, however, showed this is not the case, at least not in water.

"We performed an experiment with grains of glass under a turbulent water flow. Using a high-speed camera capable of recording about a thousand images per second, we filmed the motion of the pile from above and produced a huge amount of images," Franklin said.

"The next step was to create a computer program that opened up the movie image by image and identified each particle that had moved. By monitoring the grains, we were able to track the grains that formed the horns and the paths they followed. We discovered that they didn't all move in a single direction, as assumed by the old model. Most of them flowed around the initial pile in a circular movement, and that's how the horns took shape."

Franklin stressed that the discovery applies to dunes formed in a liquid medium, but not necessarily to dunes formed in a gaseous medium. The physical explanation for the possible difference is simple and interesting, he noted. "The previous model was based on eolian dunes, especially desert dunes. The density of air is approximately one kilogram per cubic meter. The density of a grain of sand is 2,500 kg/m^3. That's a difference in magnitude of 103, which means that to displace a grain of sand in the desert, the air must be moving very fast. So fast that when it displaces a grain, the grain is launched on a ballistic trajectory like a projectile," Franklin explained.

"The grain rises about a meter and describes a parabolic curve. The direction of flight is the main direction of the flow. Thus, the overall motion is indeed unidirectional. However, water is a thousand times denser than air at 1,000 kg/m^3. That means water and the grain of sand are within the same order of magnitude, so the water flow can displace the grain while moving much more slowly. As it does so, the grain roughly follows the motion of the water. The water flows around the pile in a circular path, and so do the grains."

The experiment showed that the previous model, which was held to be an absolute truth, does not apply to all cases. "This opens up a whole discussion about the phenomenon," he said. "Experiments will have to be done with eolian dunes to confirm whether in this case, the previous model is indeed valid. Maybe it is, but maybe it isn't. There's a lot of interest in the subject owing to the Mars missions. A small difference between Martian dunes might suggest there was water in the region in the past."

In addition to the possible applications in the long term, crude oil pumping is a much more immediate application for the research findings. Crude oil is mostly extracted from reservoirs containing sand and water, so barchans form inside pipelines and slow down the flow of oil, driving up production costs. Moreover, the sand builds up in certain places, and removal is difficult. A deeper understanding of dune formation is indispensable for solving this problem.

More information: Carlos A. Alvarez et al, Role of Transverse Displacements in the Formation of Subaqueous Barchan Dunes, *Physical Review Letters* (2018). DOI: 10.1103/PhysRevLett.121.164503

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