Dune formation

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Dunes are land formations of sand of heights, ranging typically from 1 to 500 meters which have been shaped by the wind. These topographical structures are found typically where large masses of sand have accumulated, which can be in the desert or along the beach. Correspondingly one distinguishes desert dunes and coastal dunes. Dunes can be mobile or fixed. Fixed dunes are older and are either "fossilized" which means transformed into a cohesive material, precurser to sand stone, or fixed because the average wind at their site over some period is zero. Otherwise the sand moves if the winds are strong enough, that means typically stronger than 4 meters a second.

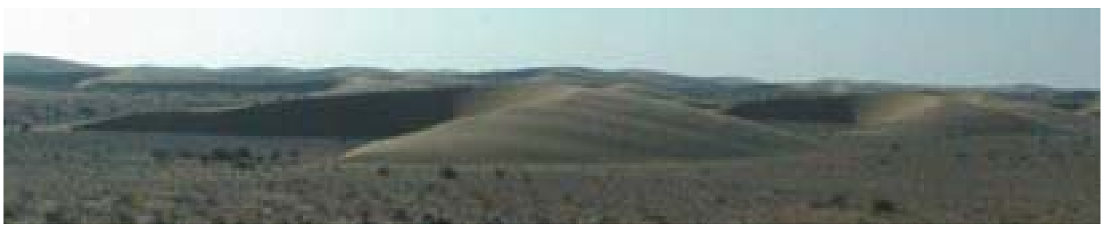

Figure 1: Barchan dunes near Laâyoune Morocco.

As we all know, the beautiful landscapes (Fig. 1) formed by dunes are characterized by very gentle hills interruped by sharp edges called brink lines, delimiting regions of steeper slope, called slip-faces, lying in the wind shadow. Depending on the amount of available sand and the variation of the wind direction, one distinguishes different typical dune morphologies that have been classified by geographers into over 100 categories. The most well-known are longitudinal, transverse and Barchan dunes. Barchans (from an Arabic word) are crescent like mobile dunes that appear when the wind always comes from the same direction and there is not much sand present. Their velocity ranges from 5 to 50 m per year and is inversely proportional to their height. If sufficient sand is available to cover all the surface, then transverse dunes appear (from the merger of many Barchans). Longitudinal dunes, i.e. along the direction of the wind, are observed when the wind direction changes periodically its direction over about 30^0. Other famous dunes are star dunes, ergs, parabolic dunes and draas.

The driving force for sand motion is the drag imposed by the wind on the grains at the surface. A given dune morphology can therefore only be understood as an aerodynamic instability close to a mobile surface. A complete mathematical description of the problem therefore needs the equation of motion of the wind velocity field coupled to an equation of motion of the granular surface. The right formulation of these equations requires a good understanding of the transport mechanism of sand. Three types of transport can be distinguished according to the size of a sand grain: creep, saltation and suspension. The only mechanism relevant for dune formation is saltation which drags grains typically of 100 μm - 300 μm diameter. The mechanism of saltation first described by Bagnolds in his pioneering work [1] consists of grains which once lifted out from their granular bed are accelerated by the wind and then impact against the surface ejecting new grains. These grains are again accelerated and eject again a splash so that the number of grains flying above the surface increases exponentially until the total momentum transfered from the air to the grains saturates to its maximum capacity. On the field these saltating grains form a sheet of grains floating typically 5 cm above the surface. The wind which typically is turbulent has a logarithmic profile as function of height, which, due to the presence of the grains, is strongly modified close to the surface. The height of the boundary layer is less than 1 cm. Using the techniques of Jackson and Hunt [2], one can calculate the shear force of the wind at the surface in an approximate form and obtain a reasonable agreement with measurements on dunes. The saturated flux of sand at the surface is a function of this shear stress and has been described by various phenomenological expressions, the first one given by Bagnold [1] and subsequent ones by Lettau and Lettau [3] and by Sørensen et al. [4]. A full description also requires taking into account the transient before reaching (or after) saturation. Together with mass conservation one can then close the system of equations, giving at the end a full set of equations of motions [5].

When the local slope exceeds a value of typically $tan\ 35^o$, the angle of repose, the sand begins to slide in form of avalanches giving a second mechanism of sand transport driven by gravity. The slip-faces all have this slope. The edges separating them from the purely wind driven regions are just given by the brink lines. Over these regions the wind field develops recirculation eddies of velocities typically below the minimum threshold for grain motion. When the saturation transient is less than the size of these low velocity regions, the sand grains get trapped. This is the principal instability underlying dune morphology, the dunes become traps of sand for sand. The typical length of the saturation transient of about 10 m also imposes that no dune below 1,5 m is stable under meteorological conditions.

Dunes have been studied on all continents and their shape, sand flux, velocity and granulometry have been presented in many publications. Several books review the subject [6]. For different morphologies one finds specific shapes and scaling laws, but systematic studies exist only for barchans. Sand fluxes are typically measured with traps, but a more sophisticated metrology (acoustic, optic) is evolving. The limitation factors are the fluctuations of the wind fields and the climate. In the arid regions of the world, in particular the poor countries in the Sahara, dune motion poses an important threat to housing, roads, fields etc. and sand removal constitutes a significant economical factor in these countries. Many empirical techniques of dune fixing and dune destruction have been developed, but mostly applied to coastal dunes which in fact are disappearing in many places, sometimes crippling the eco-system.

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