17 Types of Aeolian Sand Dunes and Their Formation

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17.1 Introduction

The accumulation of windblown sand creates sand dunes which are one of nature's most dynamics and intriguing phenomena. Sand dunes are found in most climates of the world as coastal dunes and in some arid regions. Grains of sand between 0.062 and 2.0 mm in diameter are not cohesive and therefore are easily carried by the wind. Paradoxically, finer grains of silt and clay (< 0.050 mm) are cohesive and can resist wind erosion. This property of sand is reflected in the wind threshold speed curve for sand transport (Fig. 17.1) explaining why dune sand, in most cases, is composed of fine particles between 0.125–0.250 mm.

While sand dunes, mobile and immobile, are found in almost all climates, from humid Europe [1,2], boreal Alaska [3], and Central Canada [4] to semiarid [5] and arid areas [6], more than 99% of all sand dunes are located in deserts. Less than 1% are located in humid climates and along some of the world's coastlines [7]. Coastal dunes are known to be relatively young, no older than 6,500 years, which is when the sea reached its present level after the last rapid postglacial rise. The common characteristics for all dunes, in all world climates, are that their formation indicates an abundant supply of sand-sized sediment, strong sand-moving winds, and conditions favoring sedimentation of the sand. Most of the world's sand dunes were active during the period 20,000 to 15,000 BP, known as the last glacial maximum, when wind power was much higher than in present-day wind storms [8,9].

17.2 Wind Power

Wind should not only be above the threshold velocity (Fig. 17.1) to initiate sand transport, but should also have a certain drift potential to prevent plants from growing in the sand and stabilizing it. The accepted method of quantifying wind power is by referring to the drift potential (DP) of the wind, which is based on the sand transport equation [10] in which the sand flux is directly proportional to the cube of the wind:

$$q = Ku_*^2(u_* - u_{*t}) , \tag{17.1}$$

where u_* is the shear velocity of the wind, u_{*t} is the threshold shear velocity and K depends upon variables such as grain size, sand sorting and air density. Since K characterizes variables that have little variation from one dune field to

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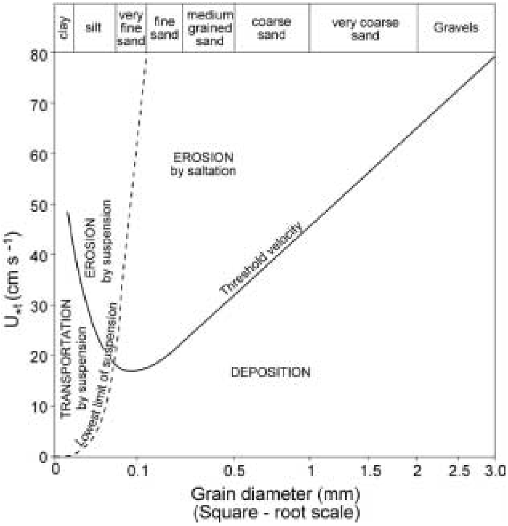

Fig. 17.1. Threshold friction velocity (U_{*t}) curve for quartz grains of different diameters (*solid line*). The broken line separates saltation from suspension (after [10])

another, the drift potential (DP) in vector units can be calculated by simplifying (17.1) and referring to the cube of the wind velocity above the threshold speed [11]:

$$DP = \sum q = \frac{u^2 (u - u_t)}{100} t \,, \qquad (17.2)$$

where q is the rate of sand drift, u is the wind velocity (in knots), u_t is the threshold velocity (in knots) and t is the amount of time the wind blew above the threshold (in %). An index of wind direction variability is illustrated by the ratio between the resultant drift potential and the drift potential (RDP/DP), where values close to one indicate narrow unidirectional drift potential, and values close to zero indicate multidirectional drift potential.

The average yearly DP forms sand roses that indicate the relative potential transport of sand from various directions. An example is demonstrated by Fig. 17.2, which shows sand roses in three sites along the coastal plain of the southeastern Mediterranean. The total yearly average DP and the ratio RDP/DP can explain mobility and stability of sand dunes mostly because the limiting factor for vegetation on dune sand is wind erosion [12,13]. When RDP/DP is low, wind energy is distributed on more than one slope of the dune and the energy exerted on each slope is lower. For that reason sand dunes with high rates of directional variability are covered by vegetation on their slopes (as in some star dunes, Fig. 17.3) while under the same DP and low rates of directional variability, the dunes are bare of vegetation.

Sand dunes in areas where the annual average rainfall is ≥ 50 mm are unvegetated and mobile under the conditions in which $DP > 1000$ and RDP/DP is

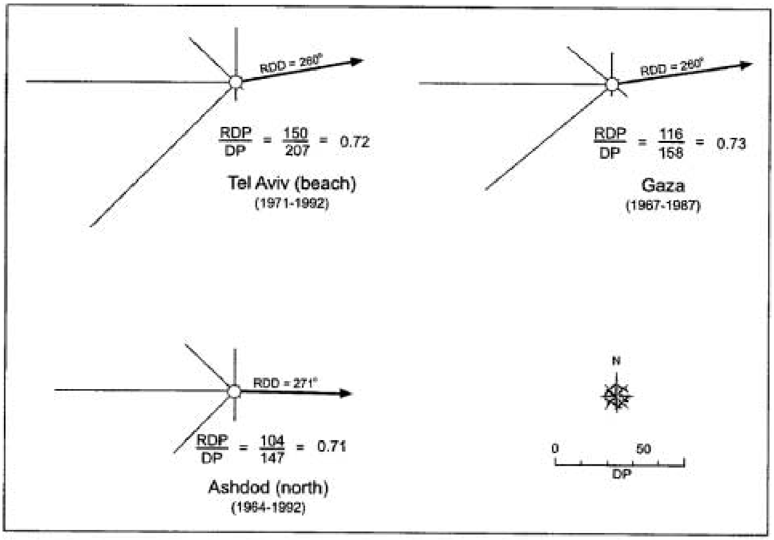

Fig. 17.2. Three sand roses of the drift potential (*DP*) vectors for three stations along the southeastern Mediterranean coast. Note the ratio of the total *DP* and the resultant drift potential (*RDP*), which is a parameter for the wind direction variability

Fig. 17.3. Star dunes in Gran Desierto, Mexico, where their slopes are covered by vegetation because of low value of RDP/DP (about 0.21 for the nearest meteorological station), in spite of the low amount of rainfall (about 70 mm on annual average). Data from [90]

close to zero, or $DP > 250$ and RDP/DP is close to one [13]:

$$\frac{DP}{1000 - (750\,RDP/DP)} > 1\,. \tag{17.3}$$

Table 17.1 gives the DP and RDP in various dune sites of the world. The table shows that rainfall is not as decisive a factor for dune mobilization or stabilization as is the DP. In the Negev Desert dunes are fully stabilized where the average yearly rainfall is 90 mm. The dunes in Sinai (east of Al-Ismailiya) and the coastal dunes in Gaza are fully active due to human impact [14]. Dunes that were artificially stabilized, such as along the Netherlands coast, will become active once the vegetation is destroyed.

17.3 Classification of Sand Dunes

The tremendous variety of sand dunes makes their classification a difficult task. Three main factors (two climatic and one sedimentary) influence the piling of sand into dunes with particular shapes:

1. Wind magnitude (above the threshold velocity), direction, and frequency.
2. Vegetation cover.
3. Grain size.

In addition, other factors – obstructions to wind flow, climatic changes manifested by dramatic change in wind direction, velocity and frequency of storms, sand availability, thickness of sand cover, and sudden removal of vegetation cover – can affect dune morphology. Because dunes are bed-forms in which a great deal of energy has been invested, daily or seasonal changes in wind direction do not easily reshape them. Therefore dune shape is the manifestation of a long-term average of wind conditions.

Distinction of sand dunes into simple (basic), compound and complex forms was suggested by McKee [15]. Simple dunes consist of individual dune forms which are spatially separate from nearby dunes. Compound dunes consist of two or more dunes of the *same* type which have coalesced or are superimposed. Complex dunes consist of two or more *different* types of simple dunes which have coalesced or are superimposed. Complex and compound are in most cases megadunes and abound in most of the world's great sand seas. Simple sand dunes are small in most cases, with wavelengths (shortest distance from one dune crest to the other) of 10 to 500 m.

Three general types of active sand dunes are classified by movement:

1. *Migrating dunes:* the whole dune body advances with little or no change in shape and dimension. Transverse and barchan dunes are the most representative specimens.
2. *Elongating dunes:* the dunes elongate and become extended in length with time. Linear dunes are the most representative specimens.

Table 17.1. Drift potential (DP), directional variability of the wind (RDP/DP), and rainfall of several dune field sites. * approximate value; N/A not available

Location, Country	DP	RDP/DP	Average yearly rainfall (mm)	Dunes status
Al-Ismailiya, Egypt (western Sinai)	62	0.47	50	Fully active
Nizzana, Israel (Negev Desert)	108	0.70	90	Fixed (fully vegetated)
Gaza, Palestine (coast)	158	0.73	400	Active (partly vegetated)
Ashdod, Israel (coast)	147	0.71	500	Semi-active (partly vegetated)
Upington, South Africa (Kalahari Desert)	560	0.66	183	Stabilized linear dunes
Port Elizabeth South Africa (coast)	951	0.49	660	Fully active with no vegetation
Newport, Oregon USA (coast)	2000*	N/A	1750	Fully active with no vegetation
Luderitz, Namibia (coast)	2300	0.85	< 100	Fully active with no vegetation
Ijmuiden The Netherlands (beach)	3999	0.51	768	Fully stabilized by vegetation, active when vegetation is destroyed

3. *Accumulating dunes:* the dunes have little or no net advance or elongation. Star dunes best represent this type.

These three types are distinguished by wind direction variability (RDP/DP) [16,17,18,19]. Migrating dunes are formed by a wind regime that is unimodal or close to a unimodal direction ($RDP/DP \geq 0.6$). The wind directions of elongating dunes are bimodal when the two modes are 90°–70° apart ($0.8 > RDP/DP > 0.5$). Accumulating dunes are formed under bimodal or multimodal wind directions when the two main modes form an obtuse angle that is about 180° ($0 < RDP/DP < 0.4$).

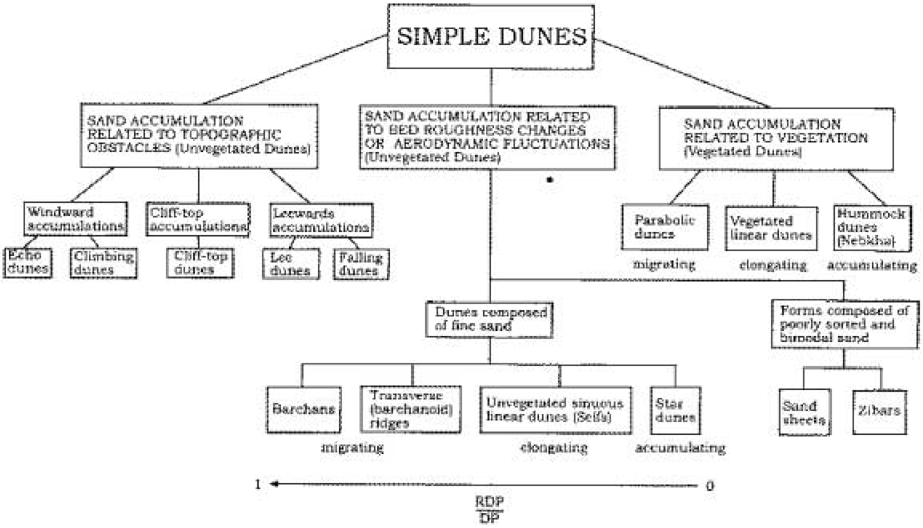

Fig. 17.4. Classification of major dune types based on dune genesis and wind directional variability (after [10])

The above classification along with a classification based on dune genesis and processes [10] is shown in Fig. 17.4. Dunes are segregated into three different categories of sand accumulation:

1. Accumulation as a consequence of topographic barriers (mostly cliffs) interfering with airflow. These dunes are not vegetated.
2. Accumulation of sand in areas of open terrain due to changes of bed roughness or aerodynamic fluctuations. These dunes are not vegetated.
3. Accumulation due to vegetation that determines dune formation and shape. All dunes in this category are vegetated. If vegetation is destroyed by human impact the reaction is either transformation to a category 2 dune type, or the formation of superimposed dunelets on top of the main dune.

The second category, unvegetated dunes that are self-accumulated, is widespread mostly in arid lands. This category is subdivided according to the grain size into sand dunes with bimodal and unimodal sand-grains. The fine sand mode of the bimodal sand dunes is within the range of the mean size of unimodal desert dune sand (0.125–0.250 mm). All dunes composed of bimodal coarse sand have a moderate aspect ratio of $h/L < 0.3$ (where h is the hill height and L is the horizontal distance from the hilltop to the point where the elevation is half its maximum). Dunes composed of unimodal, well-sorted fine sand display slip-faces, pronounced crests and a much higher aspect ratio ($1.3 > h/L > 0.3$). Despite the upslope increase in wind shear stress, the effect of gravity ($mg \sin\theta$) on grains, which is dependent upon the weight of the grain (mg) and the slope angle (θ), is stronger [20]. Bimodal sand with one coarse mode can only form *sand-sheets* and *sand-strips*. Coarse sand-sheets (also known as *zibars*) are the most common types of aeolian depositional surfaces in deserts, covering an area of 1,520,000 km^2 [21].

17.4 Dunes Accumulated and Controlled by Topographic Barriers

Topographic obstacles such as cliffs, buttes, boulders or shrubs act as baffles and induce separation of airflow into zones of acceleration and deceleration, thus producing local changes in direction and enhanced atmospheric turbulence.

When the airflow approaches the front of an isolated obstacle, such as a boulder, butte, mesa, cliff or mountain, it slows down suddenly, causing a build-up of pressure against the obstructing face [22]. The affected streamlines are forced to separate from the surface. Some of them rise and flow upwards with increasing wind velocity over the obstacle, while others make a loop and create a windward reverse-flow eddy (Fig. 17.5). The shape of the obstacle causes the flow in the windward eddy to spiral and sweep around the obstacle for some distance downwind, thus producing a three-dimensional horseshoe vortex in which the helicoidal vortex, around the windward and lateral sides of the obstacle, causes erosion [23]. The two vortices trail downwind, leeward of the obstruction, and fade out (Fig. 17.5). Unlike self-accumulated dunes, dunes that are related to

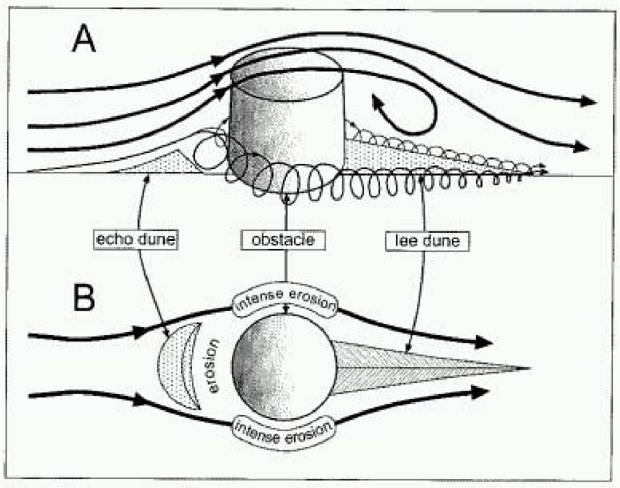

Fig. 17.5. A diagram showing the development of a horseshoe vortex in front of and around an obstruction and the resultant sand deposition. (**a**): side view; (**b**): plan view (after [10])

Fig. 17.6. Echo dune developed in front of a cliff. The extremities of the dune develop into climbing dunes and are the only places where sand leaves the dune and climbs the cliff

obstacles are static, i.e. they do not advance or elongate. Once they achieve a steady state form, the active processes of erosion and deposition do not affect their stability since the amount of sand they receive equals the amount they lose [24].

The reverse flow of the horseshoe vortex in front of a vertical obstacle (such as a cliff) causes a drop in wind magnitude at a distance of $d/h = 3.3$ (d is the horizontal distance from the obstacle upwind and h is the height of the obstacle) and a minimum at $d/h = 0.75$, which is where the two opposite flow directions meet [24]. The outcome is an accumulation of sand that evolves into a static *echo dune* (Figs. 17.5 and 17.6). No accumulation occurred between the distances of $0 < d/h < 0.3$, but erosion is induced by the reverse flow of the horseshoe vortex and on the lateral sides of the obstruction (Fig. 17.5). Wind tunnel simulation shows that a steady state is reached when the height of the echo dune is about $0.3\,h$ to $0.4\,h$ [24]. At this height the shear velocity at the windward side of the crest is slightly higher than that of the reverse flow of the horseshoe vortex on the lee side of the crest. Sand that is added to the dune from the windward side will move onto the trough between dune and obstacle and be carried by the horseshoe vortex to the rear side of the obstacle where some of it will accumulate in the ‘shadow’ of the obstacle, between the two horseshoe vortices, to form a *lee dune* (Fig. 17.5).

Lee dunes are best developed by a nearly unidirectional wind regime. At a distance where the topographic obstacle is no longer effective as a barrier, they tend to break up downwind into individual *barchans,* which are the preferred dune form in an open area unidirectional wind regime. The size of the lee dune is directly related to the size of the obstacle; the dune can be small, a few centimetres high and extending a few dozen centimetres downwind behind small shrubs or boulders, or it can attain a height of hundreds of metres and extend several kilometres downwind [23]. The term *longitudinal*, applied to lee dunes [25,26], originates from the resemblance of big lee dunes to *seif* dunes. However, according to the classification used in this paper (Fig. 17.4), seif dunes are not related to obstacles.

When the brink of the cliff is straight, without any projection, there is no convergence of flow on the lee side of the cliff but a great abatement of wind velocity. The result is, literally, *falling dunes* that in some cases mix with scree (talus) deposits [27,28].

Sand is normally incapable of climbing slopes [20]. Wind that encounters a cliff is diverted at the foot of the cliff to flow parallel to the cliff front. When the wind impinges obliquely upon the cliff, the separation eddy turns into a helical roll vortex that moves along the cliff front, causing sand transport along the foot of the cliff and preventing sand from climbing it [29]. Despite the above, aeolian sand is known to climb slopes, forming *climbing dunes.* This happens when a bell-shaped slope narrows, creating a funneling effect in which wind-carried sand is forced to climb the cliff, or where the helical roll vortex climbs the cliff through drainage channels (Fig. 17.6). Leeward of the slope crest there is a great abatement in wind velocity, resulting in *cliff-top dunes* [30,31].

17.5 Self-accumulated Dunes

Sand has the propensity of self-accumulation into mounds, or dunes, in the absence of topographic obstacles and vegetation. This tendency is due to the fact that the change from a rough to a smooth surface, i.e. from gravel to a sand patch, will cause a sharp drop in shear velocity, leading to sand deposition [32]. This process is only effective when strong, sand-laden winds are able to carry sand over a rough surface and then allow it to accumulate on the sand patch. Under gentler winds the sand is trapped over the rough surface so that a sand patch would be eroded and extended down-wind [33].

A different explanation is given by the *wave-form theory.* It speculates that a wave-like movement in the air, initiated by an irregularity in the bed, brings about variations in surface shear stress, causing an increase followed by a decrease in the sand transport rate [34]. This means that there are alternating transverse or longitudinal zones of erosion and deposition under which a bed-form shape of ridges and troughs starts developing and builds up until the wind velocity at the surface of the new mound is sufficient to remove as much sand as is deposited. In this case a steady state is formed, similar to a ripple formation [1], [34,35,36].

17.5.1 The Steady-state Dune Profile

The presence of the rudimentary aeolian bed-forms produces a number of modifications in the airflow of the atmospheric boundary layer, as both wind shear velocity and turbulence structure change when the wind blows over any mound of sand. Any such change in wind velocity has a significant influence on surface shear stress and, hence, on sand transport rates and dune morphology. On every hillock patch there is an increase in surface shear stress up the windward slope toward the crest and a decrease on the lee side [37,38,39,40]. Sand dunes, as a dynamic geomorphic system, have the attribute of negative feedback, self-regularity bedform which subjects them to periodic changes in energy (wind velocity and direction) and material (sand). Any alteration in wind and sand supply produces a change in dune morphology by forming a negative feedback which regulates the effect of that change, and brings the dune to a new state of balance whereby input and output of material and energy are equalized. This condition of equilibrium is known as a steady state [41]. A simple dune can be considered to be in a steady state when its shape and size do not change while the dune is advancing (the self-preservation criterion), i.e. when the rate of advance of all parts of the dune is constant [42,43]. A dune that is pushed out of steady state by a change in wind direction or alteration in sand supply produces negative feedback which adjusts itself to the effect of those modifications and restores a new state of balance. A final steady state does not occur because of continuing small changes in wind direction and magnitude. Therefore, all sand dunes are actually in a time-independent quasi-steady state, with little change in their configuration [44].

The first rudimentary aeolian nascent bed-form is not in a steady state; it is a result of the harmonious interrelation of wind velocity, direction and sand transport that brings the bed-form into a steady state where the rate of sand transport increases on the windward slope toward the crest in such a way as to ensure a constant and steady rate of advance at all points on the windward slope. The dune shape changes the wind shear stress above it. The change in wind speed above the dune is essential for the increased rate of sand transport on the windward side, which maintains the dune in a steady state. The change in wind velocity over the dune, measured at a particular height (z) above ground level, can be expressed as the *speed-up ratio* (A_z) [45]:

$$A_z = \frac{\bar{U}_2}{\bar{U}_1} \tag{17.4}$$

where $\bar{U}_2$ is the mean wind velocity at height z above the dunes and $\bar{U}_1$ is the mean wind velocity at the same height above a flat surface. The rate in which the speed-up ratio changes over the dune depends upon the dimensions of the dune and its shape [41]. A dune attains a steady-state shape when the speed-up ratio increases the wind shear stress in such a way that sand is eroded and carried along the windward slope while adhering to the steady-state principle (no change in shape while the dune is advancing). This rate of advance (c) depends upon the rate of erosion $\mathrm{d}q/\mathrm{d}x$ (where q is sand-transport rate per unit width and x is the longitudinal coordinate along the windward slope) and on the declination of the slope ($\tan\alpha$). In a two-dimensional configuration the above can be formulated as [42]:

$$\frac{\mathrm{d}q}{\mathrm{d}x} = \gamma c \tan\alpha \tag{17.5}$$

where γ is the specific weight of the sand in bulk. The rate of erosion is defined by the wind velocity as specified by the rate of increase in speed-up ratio, the latter depending upon the shape of the slope (Fig. 17.7). Two-dimensional profile analysis [41] and three-dimensional modeling [46,47,48] indicate that a dune's steady-state profile in a unidirectional wind regime is a low convex slope (boat-shaped) similar to the form of a barchan dune (Figs 17.7(C) and 17.8). Three different shapes of dune profiles are shown in Fig. 17.7 with the corresponding speed-up ratio for each profile (solid line). Also shown in Fig. 17.7 is the profile of the theoretical speed-up ratio (broken line) needed for maintaining a steady-state dune shape.

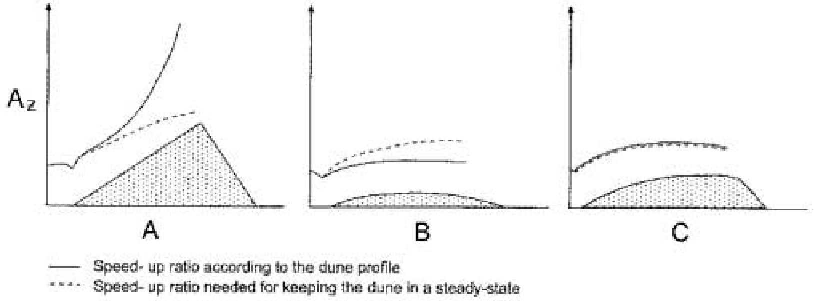

Fig. 17.7. The rate of change of speed-up ratio (A_z) over three different windward slope shapes. The solid line presents the speed-up ratio formed due to the shape of the slope. The broken line presents the speed-up ratio that would keep such a shape in steady state condition. (**a**) A uniform slope. (**b**) A small convex shape. (**c**) A bigger convex shape (for explanation see text)

When a dune's windward slope near the crest is steeper than that of a steady-state dune (Fig. 17.7(A)) the speed-up ratio on the upper windward slope attains a greater magnitude than needed to carry all the sand previously eroded from the windward slope. Consequently, sand will be eroded from the upper part of the windward slope and the crest will be lowered until a steady state is reached (Fig. 17.7(C)). A self-regulatory process can occur in the opposite direction. A bed-form can have a conformation that is flatter than that of the steady state (Fig. 17.7(B)). In that case the rate of increase of the speed-up ratio towards the crest is insufficient to prevent sand from being deposited on the windward slope; consequently the dune will grow in height until a steady state is reached (Fig. 17.7(C)). This is a self-regulatory process whereby sand deposition changes

Fig. 17.8. Oblique air view of a barchan dune. Note the convex windward slope (the left side of the dune), the steep lee slope (slip-face) where avalanches occur, and the two horns typical to barchans

the bed-form shape, which, in turn, increases the wind velocity, and gradually a steady-state form is achieved. The processes of sand accumulation and self-regulation are very short, acting until the dune achieves a steady state. Therefore, most dunes in the field fall into the categories of steady state or quasi-steady state.

Sand eroded on the windward side is deposited on the upper lee side, causing oversteepening until it reaches the critical *angle of internal friction*, which is approximately 35°. At this angle the upper lee slope is not steady and failure occurs by the formation of a series of avalanche 'tongues' (Fig. 17.9) that reduce the slope angle to 32°–33° – the *angle of repose* [10].

The profile and processes described above are typical of transverse and barchan dunes, which are *migrating dunes.* They advance by erosion on the windward slope at a rate expressed in (17.5), and deposition on the lee slope, followed by avalanche that forms a *slip-face* (Fig. 17.9).

17.5.2 Transverse and Barchan Dunes

Transverse and barchan dunes are the same dune type, migrating according to the same unidirectional-wind mechanism. It is the amount of sand available for aeolian transport that causes the difference between the two. Barchans are isolated mounds of sand, formed in limited sand supply areas which overlie coarse

Fig. 17.9. A field of barchans in the Namibian desert looking upwind. Note the avalanche tongues on the slip-face

sand or non-sandy surfaces (Figs 17.8 and 17.9); a single long transverse dune is built of many barchans that have coalesced into one long dune.

In three dimensions, the wind climbing the barchan diverges a bit from the crest towards the flanks, thus increasing the speed on the barchan sides which advance more quickly than the crest and form the typical crescentic shape (Figs 17.8 and 17.9).

The rate of advance of barchan and transverse dunes according to Bagnold [42] is in direct proportion to the rate of sand transport (q) and in inverse proportion to the specific weight of the sand in bulk (γ) and the slip face height (h):

$$c = \frac{q}{\gamma h} \, . \tag{17.6}$$

Results from measurements of the barchans' rate of advance show that the link between dune height and rate of advance is not linear. Since wind increases with height, q would not be the same for dunes with dissimilar heights. High dunes will experience relatively higher sand transport than low dunes. The data from barchan displacement in Peru [49] give this exponential relation:

$$c = 33.6\,\mathrm{e}^{-0.19h} \tag{17.7}$$

and data from Sinai [50] give another exponential relation:

$$c = 8.7\,\mathrm{e}^{-0.26h} \, . \tag{17.8}$$

According to (17.6, 17.7, and 17.8), a field of barchans will arrange themselves with the smallest dunes in front and the biggest in the back.

Most of the sand of the barchan is circulated by saltation on the windward slope and avalanching on the slip-face, where it is trapped until resurfacing again on the windward slope as the dune advances one dune length. However, a barchan loses sand through horns which are devoid of slip-faces (Figs. 17.8 and 17.9). The sand that escapes through the horns of the dune is used to create another barchan downwind (Fig. 17.10). Every barchan should be in a steady state wherein the amount of sand it loses through the horns is nearly equal to the amount of sand it gains from behind.

Fig. 17.10. A field of barchans on Mars (Near 76.7°N, 254.0°W). Note how the horns of one barchan serve as a source of sand for another barchan downwind. Sub-frame of MOC image SP2-45205 acquired on 26 July 1998. Area shown is approximately 2.4 km by 2.5 km and pixel sizes are approximately 3.3 meters per pixel. By courtesy of NASA/JPL/Malin Space Science Systems, San Diego

17.5.3 Linear Seif Dunes

A seif, an elongated dune type, is formed under bidirectional wind regimes beating the dune obliquely. Seifs are completely devoid of vegetation and possess a triangular profile with a sharp crest, which explains the term *seif* (an Arabic word for sword). Another typical characteristic of seifs is the tortuosity of their crest-lines, with their intermittent peaks and saddles (Fig. 17.11).

From its primary formation, the seif dune is affected by wind flows coming obliquely from both sides of its slopes, meeting the dune crest at an acute angle of attack and separating over the crest line. Each wind is diverted along the lee slope, after reattachment of the separated flow, to blow parallel to the crest-line in a down-dune direction. This process is referred to as the *flow diversion model* [51,52].

Fig. 17.11. Oblique aerial picture of seif dunes. Note the dunes' tortuosity and the sharp crest-line

It follows that two different processes act upon the lee slope of a dune. If the wind encounters the slope at a right angle, as is the case with barchan and transverse dunes, the flow will separate from the dune brink and create a separation bubble followed by an abrupt drop in wind velocity. Hence, deposition and formation of slip-face are the main processes acting upon the lee slope (Fig. 17.9). When, due to dune tortuosity, the wind direction is at an angle of 30°–40° to the crest-line, the flow separates obliquely to the crest-line and the reattachment flow on the surface of the lee slope is deflected to a direction parallel to the crest-line at a magnitude that is above the threshold speed [51]. Therefore, there is less deposition and more erosion and transport of sand in this segment of the lee slope (Fig. 17.12). The changing angle of attack explains why seif dunes meander. There are parts of the dune where angle of attack is acute and others where it is around 90° because of dune meandering (Fig. 17.12). Sand that is eroded and transported across the windward slope will not be deposited on the lee slope when the angle of attack is acute enough to create a strong diverted flow on the lee slope. This sand will be deposited on the lee slope when the dune meanders and, as a result, heightens the angle of attack. This process is exerted on the dune by bidirectional side-winds. Erosion by the wind from one side is offset by deposition of sand on the other side of the dune (Fig. 17.12). As was previously mentioned, only strong winds cause sand accumulation on desert surfaces. For that reason barchan dunes can also form by a bidirectional wind regime with one dominant strong wind direction (e.g. the W and SW sand transport winds in Fig.17.2). After the barchan is built up, the second, gentler

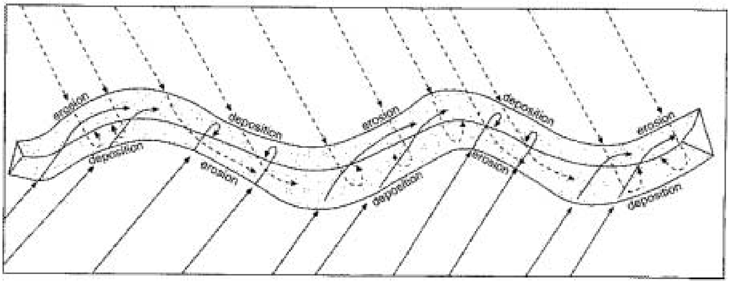

Fig. 17.12. Schematic sketch of a seif dune that is under a bidirectional wind regime (one wind direction is shown by the solid line and the other by the broken line). Note that erosion occurs on the lee side when the wind flow is diverted to flow parallel to the crest-line, and deposition when the wind encounters the crest-line perpendicularly

wind direction (e.g. the N and NW sand transport winds in Fig. 17.2) starts to affect the dune. In that case there are two main wind directions that encounter one horn of the barchan at an acute angle from both sides. Figure 17.13 is an aerial photograph of crescentic transverse dunes that are affected by a bidirectional wind regime. The strongest wind is from SW and the gentler direction is from NW. The southern horns of these transverse dunes are oriented obliquely between these two main wind directions, resulting in along-horn sand movements that elongate the horns and turn them into seif dunes (Fig. 17.13).

When seifs are formed from barchan or transverse dunes, two different aeolian bedforms are linked together in one dune system [53]. The barchan or transverse dune advances while the seif elongates. It is obvious from Fig. 17.13 that the rate of elongation is faster than the rate of advance, so it is only a matter of time until the seif dunes are the dominant dune type in this field.

17.5.4 Hybrid Dunes

In rare cases when the wind regime is bidirectional with opposing directions, the reversing wind regime will re-form a transverse dune with a complete reversing profile [42,54]. When the wind alternates from two opposite directions, the dune formed has the straight, linear, triangular shape of a *reversing dune* (Fig. 17.14). The mechanism of advance of unvegetated sand dunes can be either the transverse (barchan) mechanism, in which sand is eroded from the windward slope and deposited on the lee slope, or the linear seif mechanism, where there is also a considerable along-dune sand transport on the lee side by winds encountering the dune at an acute angle from both sides. However, in some areas the wind regime can be bidirectional where one direction is oblique to the crest line and the other is perpendicular to it. Cooper [55] noticed that Oregon coastal dunes are under such a wind regime. He termed these dunes, which resemble both transverse and linear seif dunes, *oblique ridges*. It seems more appropriate [4,56] to classify the Oregon dunes and other similar forms as *hybrid dunes*. Some see hybrid dunes

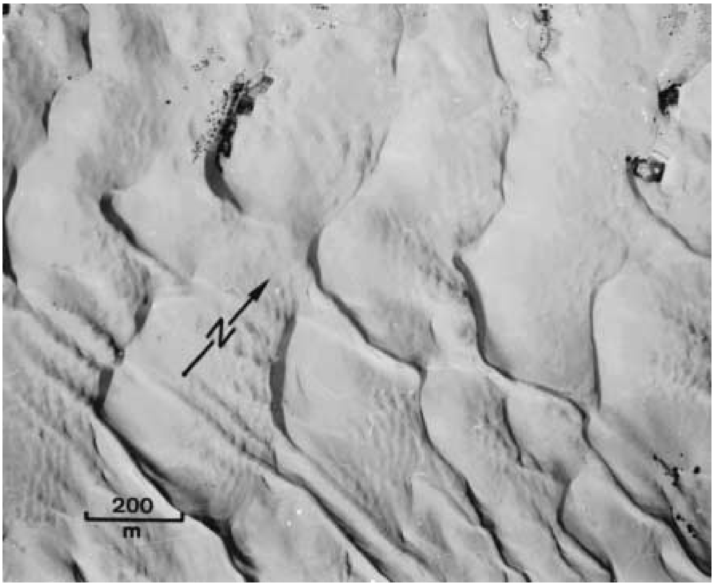

Fig. 17.13. Aerial photograph of crescent-shaped transverse dunes showing how the southern horns are turning into seif dunes

Fig. 17.14. Oblique aerial view of reversing dunes

as transverse [57] while others see them as linear dunes [58,59], although they exhibit both migrating and elongating attributes in one dune type.

Hybrid dunes can move sideways if the perpendicular wind is strong enough to form a slip-face that reaches the plinth of the dune. Pure seif dunes have small slip-faces on the lee slope undergoing erosion (Fig. 17.11) and are therefore deprived of any lateral migration [51].

The rate of elongation of the hybrid dunes is less than the rate of elongation of seif dunes because a greater proportion of the sand transport is perpendicular to the dune axis rather than parallel to it. However, hybrid dunes have a greater volume of sand per length and are therefore high dunes [4,57,58]. The confusion between hybrid and longitudinal (linear) dunes led some researchers to conclude that linear dunes migrate laterally [59,60,61,62].

17.5.5 Star Dunes

The bedforms that characterize accumulating dunes are the largest known. Star dunes are the most widespread type of accumulating dune, with sinuous arms radiating from a central, pyramid-shaped peak (Figs 17.3 and 17.15). Star dunes are formed by a wind regime with high directional variability ($RDP/DP < 0.4$) and for that reason are found in high desert latitudes where there are marked seasonal changes in wind direction [63]. Observations made in some sand seas indicate that star dunes originate as reversing or hybrid dunes in cases where sand is transported to the dune from several directions and adds to its bulk. Secondary wind directions create secondary arms that are perpendicular to the main arm of the reversing dune [63,64]. The secondary flow becomes effective once the dune increases its height and becomes exposed to winds that are below the threshold at lower elevations. Approximately 11% of all desert dunes are accumulating star dunes, and they constitute about 5% of the aeolian depositional surfaces [21].

17.6 Vegetated Dunes

Vegetation can grow on sand dunes in arid areas with less than 100 mm of annual average rainfall. The limitation of vegetation on dune sand is, first of all, human impact. The most dominant natural limitation is wind power (17.3) (Table 17.1). Rainfall is a limiting factor only where the annual average is very low (< 50 mm).

Paradoxically, vegetated surfaces cause steeper velocity gradients, and thus greater shear stress, than unvegetated surfaces. This is because vegetation causes a greater friction effect which, in turn, causes greater drag on the flow. The increased stress is not usually transferred to the ground surface, and is therefore ineffective in entraining sand. Full vegetation cover precludes aeolian entrainment but a partially vegetated canopy can only curtail particle entrainment by the wind to a certain degree [65]. Hence, dune activity can occur in the presence of vegetation.

There are several typical vegetated dune types in arid and humid areas (Fig. 17.4). Isolated clumps of vegetation act as sand traps and thus lead to the formation of *nebkhas* (coppice dunes) – hummocks that can reach up to 30 m high and 100 m across; variations in shape depend upon the shape of the canopy. They are considered to be static bedforms which change in shape as the

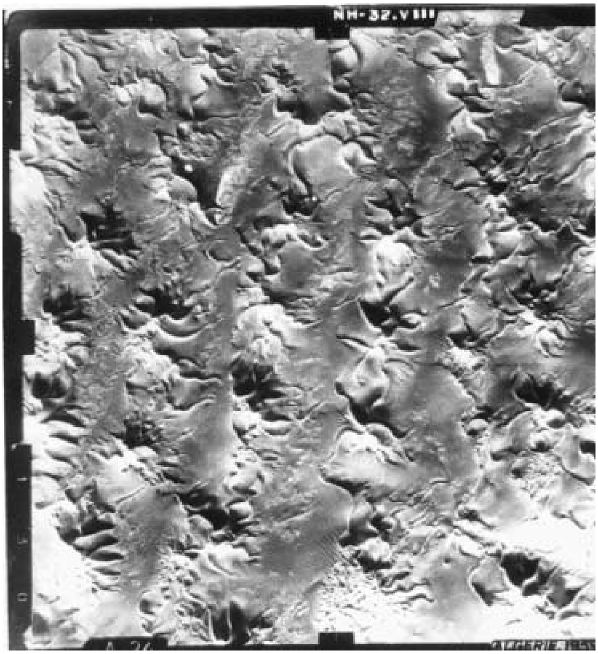

Fig. 17.15. Aerial photograph of star dunes. Note the radiating arms from the dune central peak. The main arms are from left to right and the secondary are perpendicular to them

vegetation changes with time. Experiments made by Hesp [66] demonstrated that dunes formed by the effect of isolated plants are similar to those formed by sand accumulation due to obstacles (Fig. 17.5).

17.6.1 Vegetated-linear Dunes

This dune type belongs to the group of elongating sand dunes found in many deserts of the world (Australian deserts, the Kalahari, Indian deserts and the Negev). Vegetated-linear dunes are low with rounded profiles. They range in height from a few metres up to dozens of metres. Vegetation covers them, sometimes entirely, and sometimes abundantly on the plinth and lower slopes but very sparse or absent on the crest. Those that are fully covered by vegetation have become partly or wholly stabilized. Vegetated-linear dunes may run in parallel for scores of kilometres (Fig. 17.16). An exclusive attribute of vegetated-linear dunes is the tendency for two adjacent dunes to converge and continue as a single ridge. Convergence is in the form of a Y-junction (the tuning fork shape; Fig. 17.16) commonly open to formative winds [67]. Vegetated-linear dunes are distinguished from seif dune by: 1) coextension along the strongest dominant wind direction; 2) the cover of vegetation; 3) straight alignment with no tortuosity; and 4) Y-junctions. However, when vegetation is removed, the creation of sec-

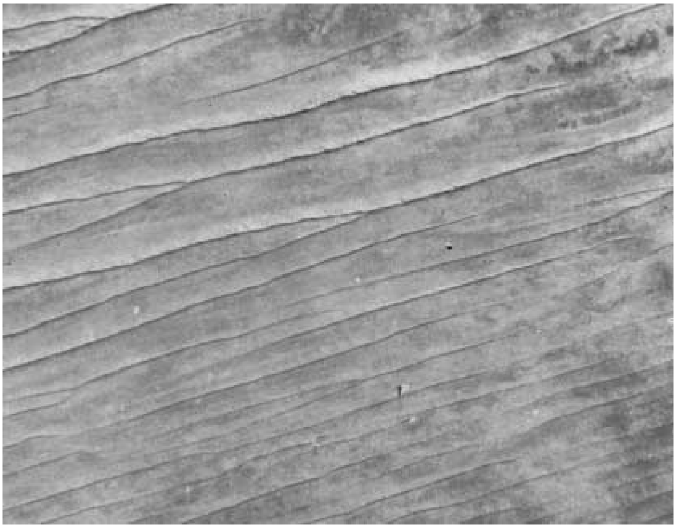

Fig. 17.16. Aerial photograph of vegetated linear dunes. These linear dunes elongate in the direction of the dominant, strong wind. Note the straight alignment of the dune (different from the meandering seif of Fig. 17.11) and the Y-junctions, which indicate wind direction from left to right

ondary, superimposed transverse dunelets with slip-faces facing downwind may change the normal low shape and rounded profile of the vegetated-linear dune (Fig. 17.17). Destruction of vegetation on vegetated-linear dunes that change their azimuth of alignment on the order of 16°–25° occurs when they converge to form a Y-junction, causing the formation of seifs (Fig. 17.17). As stated before, seif dunes form and develop under bidirectional wind regimes. Therefore, after the destruction of vegetation, the transformation takes place in those areas (Y-junctions) where vegetated-linear dunes became obliquely aligned to the strongest dominant wind.

It can be concluded from the above that vegetated-linear dunes undoubtedly owe their form and development to the vegetation cover – an important factor in the mechanism of their formation. It is worthwhile to stress that the vegetated-linear dunes in the southern and eastern Simpson Desert are located leeward of mounds that are adjacent to playas [68]. Some southwest Kalahari linear dunes also originate from pan-fringing lunette dunes [69]. In northeastern Arizona they are formed downwind of a protrusion in the cliff [70].

17.6.2 Parabolic Dunes

Parabolic dunes are mostly found in humid and cold areas. These dunes are U-shaped (parabolic) with the arms pointing upwind (Fig. 17.18). Parabolic dunes can be active and transgressive or fully stabilised and inactive. Most work on parabolic dunes and their formation was done in humid areas. However, parabolic

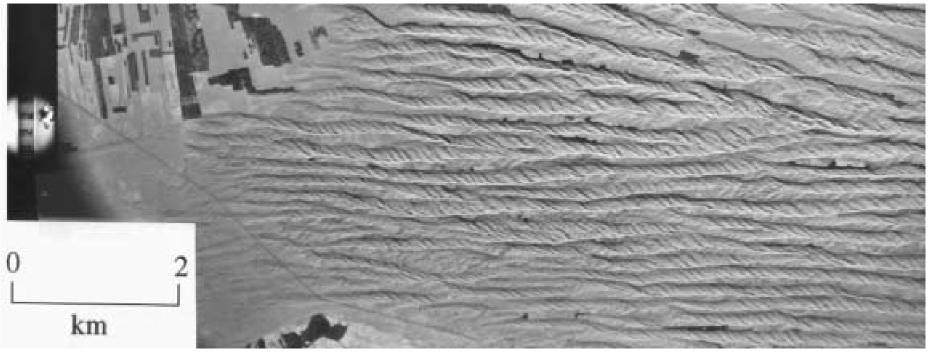

Fig. 17.17. Aerial view of linear dunes that have reacted to destruction of vegetation by grazing and trampling. Note the braided pattern of small dunelets that formed after the vegetation was destroyed. Seif dunes in the upper part of the photograph resulted from a change of 16° to 25° from the linear dune alignment because of the Y-junction

Fig. 17.18. Oblique aerial view of a parabolic dune. The wind is from right to left pushing the apex of the dune forward and leaving behind the two tails

dunes are also formed in arid and semiarid areas where vegetation is present, such as in the Jufara Desert of Arabia [71], the semiarid areas of Arizona [72], the Thar Desert of India [73] and the Kalahari desert in South Africa [5].

The mechanism of parabolic dune formation in coastal humid areas is due to the fact that vegetation is more easily established at the base of the dune near the water table. Vegetation or dampness along the lower sides of the dune retards sand motion and both are considered to be anchors. Vegetation in parabolic dune formation is said to protect the less mobile arms against wind action, thereby allowing the central part to advance downwind [74,75,76,77,78]. In this way the advancing apex leaves behind trailing ridges that elongate and turn the dune into a hairpin form [76]. Some see the U-shaped dune as a further development of a spot blowout [79,80].

It was recently found that barchan and transverse dunes turned into parabolic dunes in areas where the human impact was reduced or curtailed (Fig. 17.19). As mentioned above, the limiting factor for vegetation on dune sand is wind erosion. Accordingly, vegetation should be able to germinate and sprout on those areas of the dune that have little or no erosion. The rate of sand erosion or deposition is proportional to the tangent of the angle of inclination of the dune surface (17.5). According to the profile of barchan or transverse dunes (Fig. 17.8) erosion on the windward slope of the dune diminishes gradually toward the crest, which is an area of neither erosion nor deposition. Hence, once human impact stops, vegetation will recover on the barchan crest, thereby starting the process of transformation of these dunes into parabolic ones [81] (Fig. 17.19). The pioneer plant in this process of recovery is *Ammophila arenaria*, which is the hardiest shrub in shifting sand areas, able to withstand transport and burial by sand-baring erosion [82,83].

The dynamics and steady state of barchan or transverse dunes are disturbed once vegetation clutches at the dune crest. Some of the sand that is eroded from the windward side is trapped on the crest by clumps of *Ammophila arenaria* and is not deposited on the lee side. Sand deposition on the crest gradually changes the profile of the windward side of the dune from convex to concave (Fig. 17.19). The rate of wind erosion on the windward side of parabolic dunes increases because the airflow tends to compress when encountering the concave slope, both vertically and horizontally, and the velocity gradient above the dune increases [84]. Such a flow over the concave parabolic dune is characterized by funneling which strengthens the bed scour. Once vegetation is established, the dune will advance with sand eroded from the concave, windward slope, becoming trapped by the vegetation on the crest and the lee slope. The strong bed scour on the upper windward slope undercuts the shrubs and exposes their roots, thus forming a knife-edge shape at the inner apex of the dune, which is supported by the exposed roots [76]. The knife-edge shape divides the windward erosional slope from the vegetated depositional face. Where undermining breaks the edge, a wind channel may cut through [74]. Hence, the parabolic dune advances by undermining the frontal row of vegetation on the windward part of the crest. This last mechanism differs from that presented in the theory based on the anchoring of trailing arms by vegetation and the relative high advance forward of the central apex.

17.6.3 Foredunes

Foredunes are the most commonly found vegetated sand ridges on sandy backshores where pioneer vegetation can grow and trap aeolian sand (Fig. 17.20).

Fig. 17.19. Parabolic dunes (looking downwind) formed from transverse and barchan dunes a few years after the human impact was significantly reduced. The picture shows the bare windward slope of the dune, which is being eroded. Vegetation has recovered preeminently on the crest where there is little erosion

Foredunes develop into continuous vegetated ridges, which lie parallel to coastlines exposed to onshore wind energy. The foredune is the only dune type that involves the exchange of sand with the beach. Other coastal dunes are mostly transgressive types (barchan, transverse, and parabolic dunes), formed when sand is transferred inland where foredunes are absent, or through blowouts (wind-excavated gaps through which sand is transport landward) in the foredune ridges [85].

Two types of foredunes are distinguished by Hesp [86] – incipient and established. The incipient foredunes are newly developing dunes formed by the trapping of sand in pioneer plant seedlings (mostly *Ammophila arenaria*). Incipient foredunes are small (less than 2 meters high) and may be seasonal if formed in annual plants. Established foredunes develop from incipient foredunes when other vegetation species, generally woody plants, colonize the foredune. They can reach heights of up to 30–35 m but in most cases are less than 20 m [87]. Foredunes are undermined by storm waves, a process followed by some avalanching and retreat of the dunes' seaward slope. Between eroding storms, sand returns to the dune slopes in a recovery cycle [88].

Established and densely vegetated foredunes with no blowouts can obstruct the transmission of sand inland. Foredunes were formed on the west coast of North America after the introduction of *Ammophila arenaria* more than 100 years ago. The establishment of the foredunes cut off the sand nourishment to the coastal dunes. As a result, the sand surface leeward of the foredunes deflated to the level of the water table [82,89]. Erosion of the foredunes, which

Fig. 17.20. Foredune about 5m high formed on the backshore where pioneer vegetation can thrive

is commonly known to begin when vegetation is disrupted by human activities (trampling, traffic, fire or for pasturing livestock) may form blowouts.

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