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Parabolic Dunes: Distribution, Form, Morphology and Change

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Abstract: Parabolic dunes, which are widespread in some cold, lacustrine and coastal environments, also occur in some of the world's drylands and are associated with some vegetation cover and/or high groundwater levels. Typically they are some hundreds of metres wide, and some have long trailing arms. Under conditions of drought, vegetation removal, and groundwater depletion they may become activated and be transformed into transverse and barchanic forms.

Key words: Dune, drylands, barchans, vegetation cover, groundwater.

Parabolic dunes are hairpin-shaped aeolian landforms with the nose pointing downwind. They were described by Hack (1941, p. 242) as:

> "…long, scoop-shaped hollows, or parabolas, of sand, with points tapering to windward. The windward slope is much gentler than the leeward slope. Such dunes form by the removal of sand from the windward hollows by the wind and the deposition of sand on the leeward slopes."

Hack drew a distinction between 'parabolic dunes of deflation' caused by deflation of a pre-existing sand layer, and 'parabolic dunes of accumulation' which occur where sand is actively deposited by the wind. Parabolic dunes, which may have a U-shaped or V-shaped form, have three basic features: a depositional lobe on the downwind side, trailing arms or ridges, and a deflation basin between the trailing arms (see Goudie and Wells, 1995). The wind regimes associated with parabolic dunes are generally regarded as being unimodal or acute bimodal.

With regard to parabolic dune migration rates, in Saskatchewan, Canada, Hugenholtz *et al*. (2008) found that over a 60-year period, parabolic dunes migrated at average rates of around 3.3-3.5 m per year. The migration of some parabolic dunes in Colorado has shown temporal variability, with rates in dry years (30 m per year) being about six times those in wet years (Márín *et al*., 2005). Indeed, the occurrence of mega-droughts is very important in determining the degree of dune activity in the western USA (Hanson *et al*., 2009). Parabolic dunes in Oregon move at rates of 2.0-2.8 m per year, while those in North Queensland move at rates of between 5.6 and 6.4 m per year (Pye and Tsoar, 1990, p. 204).

Distribution

Many parabolic dunes are associated with colder environments (Koster, 1988) and humid sea and lake coastlines (McKenna, 2007; Luna *et al*., 2011), including those of Lake Michigan (Hansen *et al*., 2009), the coastal plain of South Carolina (Wright *et al*., 2011), and Queensland (Pye, 1993). However, they also very widespread in arid and semi-arid areas (Goudie, 2013). Dune fields occur in the great plains of North America from the Canadian Prairies in the north down to Texas in the south (e.g. Hack, 1941; Muhs, 1985; Halsey *et al*., 1990; Marín *et al*., 2005; Halfen *et al*., 2010; Hanson *et al*., 2009; Hugenholtz *et al*., 2008; Forman *et al*., 2009). Figure 1 shows parabolic dunes from White Sands, New Mexico, and clearly demonstrates both the range of sizes and the elongated nature of some of the arms. Figure 2 shows parabolic dunes from near Rock Springs, Wyoming, and shows relatively active noses and near parallel trailing arms. Particularly fine examples are also evident on the coastline of north east Libya near Adjabiya (Fig. 3). Parabolics also occur sporadically in parts of Australia, including the Mallee and the Big Desert of Victoria (Hesse, 2011), in the Qurayyah sabkhas (Edgell, 2006) and the Al Jafurah sand sea of eastern Arabia (Anton and Vincent, 1986). Figure 4 shows densely clustered active lobate dunes from the edge of the coastal sabkhas in that area. Parabolic dunes are also found in some formerly more arid parts of South America, such as Roraima (Latrubesse and Nelson, 2001) and the Bolivian Chaco (Latrubesse *et al*., 2012). Examples are also

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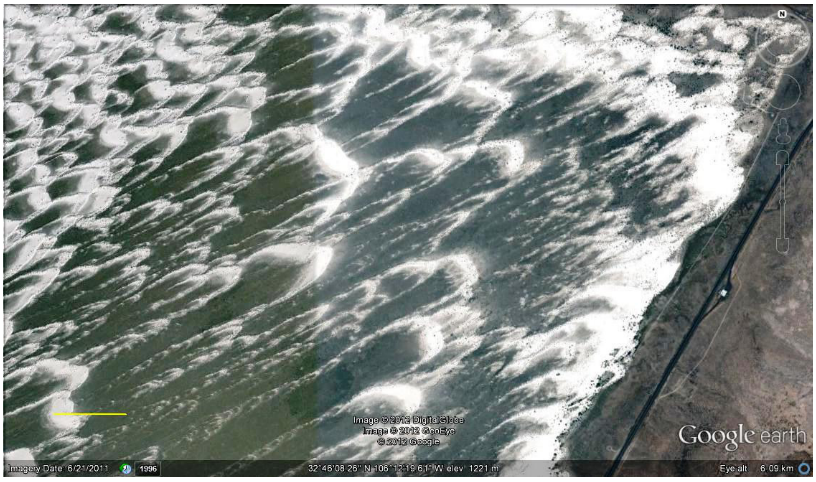

Fig. 1. Dunes from White Sands, New Mexico, USA. Scale bar is 0.5 km. Note the active noses, and the long trailing arms, some of which are composed of strings of micro-parabolics. Courtesy of Google Earth and Digital Globe (Copyright, 2012).

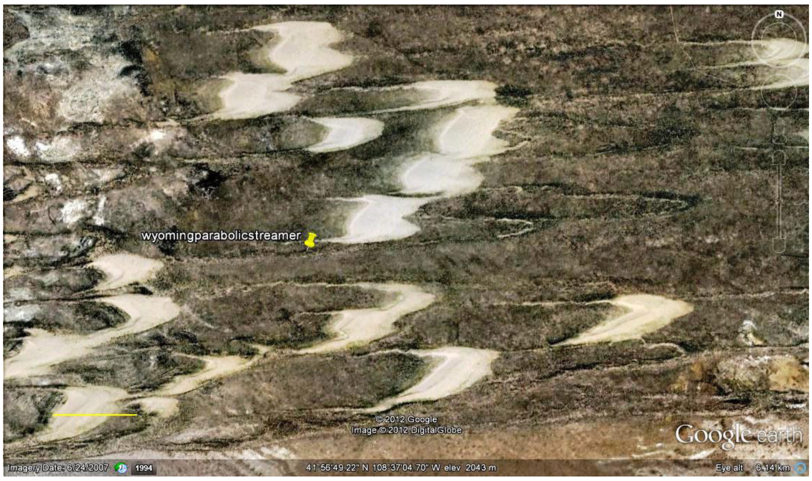

Fig. 2. Dunes from north of Rock Springs, Wyoming, USA. Scale bar is 0.5 km. Note the sharp, active noses, and the near parallel trailing arms. Courtesy of Google Earth and Digital Globe (Copyright, 2012).

Fig. 3. Large parabolic dunes developed on the coastal plain of Libya. Scale bar is 0.5 km. Courtesy of Google Earth and Digital Globe (Copyright, 2012).

Fig. 4. Densely packed parabolic dunes with relatively rounded noses on the edge of the coastal sabkhas in eastern Saudi Arabia. Scale bar is 0.5 km. Courtesy of Google Earth and Digital Globe (Copyright, 2012).

known from the fog belt of southern Peru, where fog moisture plays a significant role, while in the Salar de Uyuni in Bolivia, the parabolic dunes are composed of halite (Svendsen, 2003). One desert area where parabolic dunes make up a substantial proportion (c 29%) of the dune area is the Thar of India and Pakistan. This is a relatively low wind energy environment, which is also relatively moist and vegetated. These dunes form rake-like forms (Fig. 5).

Morphology and Structures

Pye (1993) sub-divided parabolic dunes on the basis of their length:width ratios, 0.4 for *lunate* types, 0.4-1.0 for *hemicyclic* types, 1.0-3.0 for *lobate* types, and >3.0 for *elongate* types. Verstappen (1968) suggested that in the Las Bela area of southern Pakistan, parabolic dunes could become so elongated as to be one mechanism for the formation of linear dunes. In Table 1 data are presented for the widths of a sample of 20 parabolic dunes from a range of sites in different parts of the world. The mean widths vary from 71 to 555 m. Compound parabolic dunes in the Thar have mean lengths of 2.6 km and a mean width of 2.4 km (Breed and Grow, 1979, p. 277). Parabolic dunes may have partially vegetated parallel arms and the less vegetated nose may be as much as 10-70 m high.

A classification of parabolic dunes forms is provided by Wolfe and David, 1997). They recognised that some individual parabolics may be open upwind or closed by a back ridge, this having formed by sand blown out of the

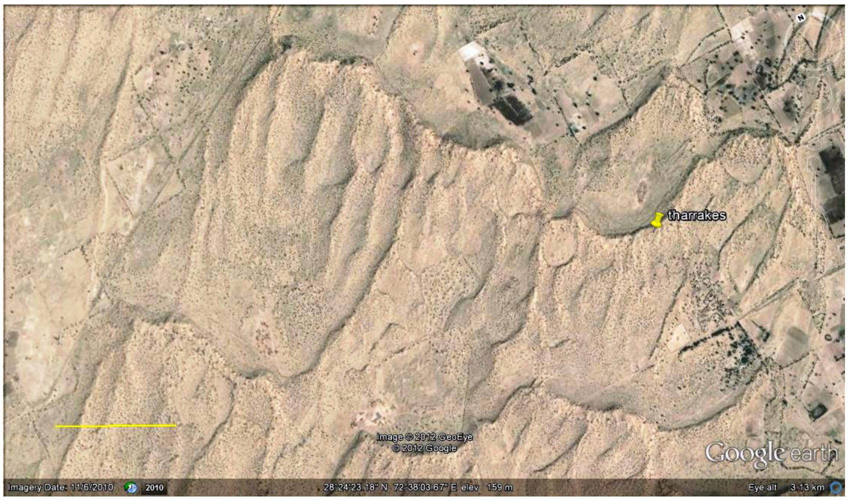

Fig. 5. Rake-like parabolic dunes from the Thar Desert, Rajasthan, Inida. The scale bar is 0.5 km. Courtesy of Google Earth and Digital Globe (Copyright, 2012).

Table 1. Parabolic dune widths (m)

Location	Latitude	Longitude	Range	Mean
Grande Prairie, Alberta, Canada	54° 56′ 54N	118° 20′ 50W	132-339	232
Crane Lake, Canada	50° 05′ 52N	108° 59′ 09W	89-217	148
Moses Lake, WA, USA	47° 03′ 29N	119° 18′ 38W	57-191	125
Hanford, WA, USA	46° 31′ 05N	119° 20′ 31W	84-328	146
Snake River, ID, USA	43° 58′ 50N	111° 58′ 08W	44-289	128
Winnemucca, NV, USA	41° 03′ 53N	118° 03′ 56W	77-213	150
Rock Springs, Wyoming USA	41° 56′ 49N	108° 37′ 04W	127-352	209
San Rafael, Utah, USA	38° 36′ 33N	110° 33′ 43W	40-120	71
Great Sand Dunes, CO, USA	37° 41′ 37N	105° 34′ 48W	31-257	93
Navajo, Arizona, USA	36° 13′ 08N	111° 08′ 59W	64-206	129
White Sands, NM, USA	32° 46 08N	106° 12′ 19W	80-345	179
Adjabiya, Libya	30° 51 31N	20° 06′ 56E	372-1042	555
Thar, Pakistan	27° 55′ 18N	70° 47′ 10E	134-523	284
Thar, India	28° 46′ 06N	73° 36′ 03E	129-810	256
Big Desert, Victoria, Australia	35° 38′ 37S	141° 09′ 33E	360-947	522
Jafurah, Saudi, Arabia	25° 54′ 39N	50° 00′ 11E	90-313	181

deflation depression. They also showed that some dunes are more filled in with sediment than others. They suggested that unfilled parabolic dunes have narrow heads and back slopes and have resulted from a relatively limited supply of sand, whereas partially filled and filled dunes with prominent heads and back slopes develop in areas of greater sand supply. Finally, they give examples of merged (compound) and superimposed dunes. They may occur in clusters, creating rake-like forms, most notably in the Thar Desert of India (Allchin *et al*., 1978). In the Big Desert of Victoria, Australia, they are an important component of transverse ridges.

Parabolic dunes have lee-side deposits composed of concave-downward strata that develop from grainfall on a cohesive slip face and are inter-bedded with avalanche cross-strata. They tend to contain structures that are indicative of moisture (e.g. adhesion laminae) and vegetation (e.g. root tubules) (McKee, 1979, pp. 94-96; Halsey *et al*., 1990). They contain few high-angle strata among their foreset beds and on the windward side of each dune the strata have notably low angle dips (McKee, 1966, p. 60). In the miliolites of Saurashtra, India, lithified parabolic dunes contain diagnostic hump cross-bedding structures (Khadkikar, 2005).

The Role of Vegetation and Groundwater

Vegetation or dampness in the lower sides of parabolic dunes retards sand motion and so functions like an anchor. Vegetation also protects the less mobile arms against aeolian processes, thereby allowing the central section to advance downwind to produce the hairpin form. Blowouts, 'the prototype of the golf bunker' (Cooke *et al*., 1993, p. 360), may occur in the nose of the dune. If vegetation cover increases or wind velocities slacken, parabolic dunes may replace more active forms such as barchans (Tsoar and Blumberg, 2002; Yizhaq *et al*., 2007; Wolfe and Hugenholtz, 2009; Ardon *et al*., 2009; Reitz *et al*., 2010; Pelletier *et al*., 2009). In the Canadian Prairies, changes in precipitation amounts and decreases in wind velocity have led to increasing dune stability since the mid-1900s (Hugenholtz and Wolfe, 2005), while over the last few hundreds of years relatively stable parabolic dunes have tended to replace active barchans (Wolfe and Hugenholtz, 2009). Conversely, there are examples in the literature of parabolic dunes losing their vegetation and turning into active transverse dunes (Barchyn and Huegnholtz, 2012). An interesting analysis of the transition between barchanoid ridges and parabolic dunes in the White Sands, New Mexico, has been undertaken by Jerolmack *et al*. (2012). They argue that dune form is influenced by the internal boundary layer of the dune field. At the upwind margin of a dune field, the dunes themselves cause an abrupt increase in surface roughness. This thickens downwind, causes a spatial decrease in the surface wind stress, which in turn leads to a downwind decline in sand flux.

At a crucial threshold, the declining sand flux triggers vegetation growth, for vigorous sand movement prevents the establishment of plants (see also, Rasmussen, 2012 and Hugenholtz *et al*., 2008). The presence of this vegetation leads to the growth of parabolic dunes, a process that has been modelled by Duran *et al*. (2005), Baas and Nield (2007) and Nield and Baas (2008). Nishimori and Tanaka (2001) argued that where there are strong winds and large amounts of sand, transverse dunes (including barchans) will dominate the system, whereas where there is less sand supply and lower velocity winds parabolic dunes will prevail.

Parabolic dunes tend to occur in areas with high groundwater levels, such as on the margins of playa lakes and coastal sabkhas. However, because salinity affects vegetation growth, areas with lower salinity may have a larger vegetation biomass to encourage parabolic dune accumulation (Langford *et al*., 2009).

Conclusion: Parabolic Dunes and Desertification

The importance of vegetation cover in areas covered with parabolic dunes, such as the Thar Desert of India and Pakistan, the Canadian prairies or the USA High Plains, suggests that such factors as droughts and human disturbance may cause rapid changes of state to occur (Hugenholtz *et al*., 2010; Hugenholtz and Wolfe, 2005; Marín *et al*., 2005), not least as certain key thresholds are crossed. There is certainly clear stratigraphic evidence that parabolic dunes have undergone repeated phases of activity and stability at different points in the Holocene (e.g. Catto and Bachhuber, 2003) in response to phases of drought (Forman and Pierson, 2003; Forman *et al*., 2006; Forman *et al*., 2009). The limited data available also suggests that they can migrate at fast rates. Future anthropogenic climate changes may lead to changes in precipitation, vegetation cover, sand supply, groundwater levels, and wind energy that could impact upon parabolic dunes. The reduction in groundwater levels caused by over-pumping of aquifers is another means by which parabolic dunes could be replaced by rapidly moving barchans, whereas in the Brazilian Amazon, parabolic dunes have been reactivated by fire (Nelson, 1994) and in Hungary they have been reactivated by agricultural land use (Kiss *et al*., 2009).

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