Facies Models 9. Eolian Sands

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Summary

Facies models for extensive eolian sand deposits must be based on the characteristics of modern ergs ("sand seas"). Peripheral areas of ergs, where supply of sand is sparse, are characterized by barchans and longitudinal dunes: neither of these seems very likely to be preserved in the geological record. The central parts of ergs, where accumulated sand thickness reaches several hundred metres, are composed of complex pyramidal dunes (draas) with superimposed complex transverse dune types. Almost nothing is known by direct observation of the cross-bedding formed in such dunes, but it is possible that it is not as variable as the complex external morphology might suggest.

Identification of ancient sandstone formations as eolian is based mainly upon one major criterion: the very large scale and relatively high angle of the cross-bedding. In many cases minor indicators, such as eolian ripples (orientated at large angles to the trend of the major foresets), avalanch scours, animal tracks, soft-sand faults, raindrop impressions, etc., are also present. Negative evidence is equally important: the only known alternative model, that of a submarine tidal sand-wave field, is *not* known to produce large scale, high angle cross-bedding: it probably produces medium-scale cross-bedding resulting mainly from migration of megaripples or sand waves of relatively small scale, superimposed on the large scale features. The cross-bedding probably shows at least some bipolar orientation of cross-bed directions, a feature absent from all classic ancient eolian sandstones. Furthermore, in the tidal sand wave model, sand deposits are associated with muddy sediments bearing a marine fauna, and this is not the case in the classic ancient eolian sandstones of the western U.S.A. and elsewhere.

Introduction

Eolian sandstones have fascinated sedimentologists, mainly because of the immense scale (up to 35 m) of the cross-bedding associated with dune migration. Recently, however, some of the "classic" eolian units, particularly the Navajo Sandstone, have been reinterpreted as shallow marine. These reinterpretations have been based upon a comparison with tidal ridges and sand waves on the present Continental Shelves. It therefore seemed appropriate in this facies model series to examine eolian sands, and to see what (if any) foundation the reinterpretations may have. A second purpose is to point out that there is no well documented, published account of an ancient Canadian eolian sandstone - perhaps an examination of eolian features will direct attention to possible Canadian examples.

In this paper, we will describe modern deserts and dunes, and then assemble information from the classic ancient examples, mostly from the South-western U.S.A. We will also describe briefly the large sand waves and tidal ridges on modern Continental Shelves, and review the controversial interpretations.

Modern Eolian Sands

Modern eolian sands are found in two main settings: sandy deserts and coastal dunes directly associated with sandy beaches. Of these the deposits of sand in deserts are by far the most extensive. Arid and semi-arid regions occupy about one third of the present land surface and comprise three main sedimentary environments: alluvial fans and ephemeral streams, inland sebkhas or playas, and sandy deserts, also called "sand seas" or ergs. Much of the area of modern deserts is composed of eroding mountains (40%) and stony areas (10 to 20%) where erosion, rather than deposition, is taking place, but on the average sandy deserts form about 20 per cent of the area of modern deserts (Cooke and Warren, 1973, p. 52-53). As our ideas about modern environments tend to be strongly influenced by the examples with which we are personally familiar, it is worth noting that the desert areas of North America are not at all typical of those of the rest of the world: in America alluvial fans are much more important (30%) and sandy deserts much less important (less than 1%) than in other major deserts.

The largest desert in the world is the Sahara (7 million km²). Traditionally it has been explored by the French, who have recently made good use of both conventional aerial and also satellite photography (e.g., Mainguet and Callot, 1974, Mainguet, 1976; also Wilson, 1971, 1972, 1973). The Sahara includes several major ergs, arranged in three main belts. Individual ergs cover areas as large as 500,000 km² (twice the area of Nevada): they are generally located in basins (both physiographic and structural) with a long history of sedimentary accumulation, including extensive fluvial deposition in Tertiary and Pleistocene times. The modern eolian deposits, however, are rarely more than 100 m in thickness.

Wilson (1971) found that ergs do not generally develop in areas of confluence of wind patterns: instead the predominant winds cross the ergs in more or less parallel lines. The main reason for the accumulation of sand in ergs seems to be the presence of a topographic depression, and the trapping action that the dunes themselves have on the movement of sand, once accumulation is initiated. Mainguet and Callot (1974) made a study of the Fachi-Bilman Erg, based on extensive air and satellite photography. The erg is situated in the southern Sahara, in a region of easterly trade winds. The trade winds are deflected by the Tibesti massif, and the erg is situated on the southwestern side of the massif, where two wind streams converge (Fig. 1). Within the erg, there is a definite spatial zonation of dune types. Barchans are found on all sides of the erg, forming an outer zone of relatively small, mobile bed forms in areas not yet fully "saturated" with sand. Inward, the barchans coalesce and are transformed into larger, less mobile forms: first sinuous seif dunes and then fully developed longitudinal dunes (called silks). In the upwind, central part of the erg is a zone of large pyramidal dunes (oghurds or draas) of considerable height (more than 100m) and width (0.5 to 1.5 km). Small seifs radiate in several directions from each of these large sand masses, which may nevertheless themselves be arranged in regular geometric patterns or rows. The main zone of longitudinal dunes (silks) is on the lee side of the central oghurds.

This particular erg appears to be fairly typical. As Wilson (1972) has pointed out, there are three main scales of eolian bed forms: small ripples (which are flatter than ripples formed in the water, and have more regular crest-lines), transverse and longitudinal dunes, from 0.1 to 100 m high, and complex pyramidal types, with heights of 20 to 450 m. The observed dune patterns are extremely complex, even in regions (such as the Fachi-Bilman Erg) characterized by relatively constant (trade) winds. It seems that large accumulations of sand (draas) modify the local wind patterns both by topographic deflection and by extreme heating of the sand surface, which produces convective circulation of air (more than 70% of the heat is transferred from the sand to the air during the day).

Much of the area of ergs is covered by only a thin veneer of sand, locally piled into barchans or longitudinal dunes. For example, Wilson (1973) estimated that in the Simpson Desert (Australia), an erg composed almost exclusively of longitudinal dunes, the *average* thickness of sand was only one metre, though individual dunes rise to 30 m. Eolian sands in such areas are much less likely to be preserved than those in areas dominated by draas, where average sand thickness may be over 100 m.

Our knowledge of the internal structures of modern desert dunes is still somewhat limited, and is due almost entirely to the work of McKee (1966; McKee and Douglass, 1971; McKee and Tibbitts, 1964; McKee and Moiola, 1975; see also Sharp, 1966). For example, the structures of longitudinal dunes, the commonest dune type in modern deserts, are known only from pit sections (each about 1 m²) of a single small seif dune (14 m high) in the Zallaf sand sea of Libya (McKee and Tibbitts, 1964). The most detailed of McKee's studies have been of various dune types in the White Sands dune field of New Mexico. This dune field is not typical, both because it is small (700 km²) and because the sands are composed of gypsum which is relatively easily stabilized by occasional wetting during rains.

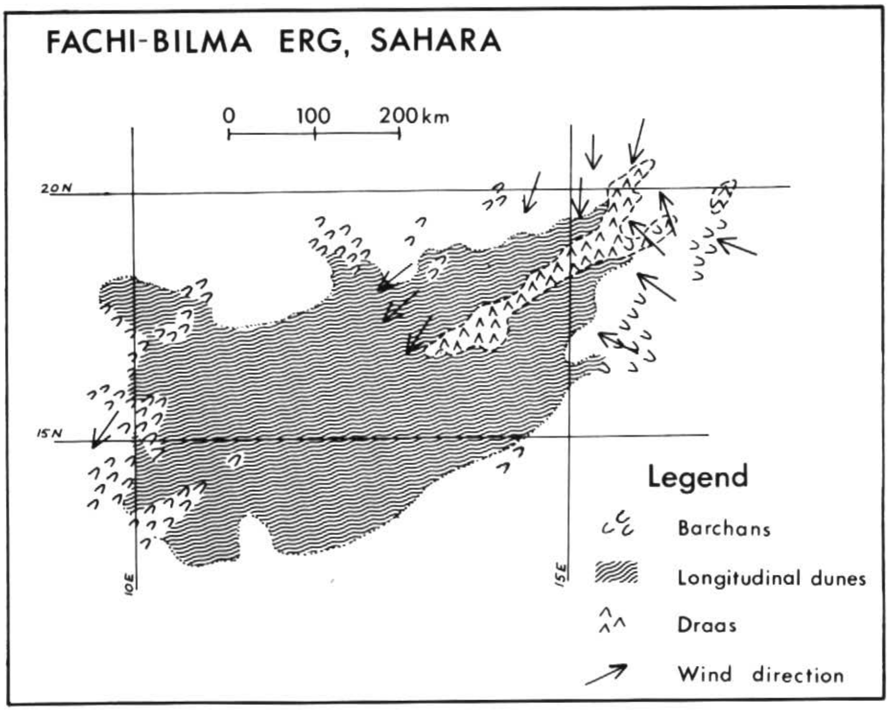

Figure 1
Distribution of dune types and wind directions in the Fachi-Bilma Erg, southeastern Sahara (modified from Mainguet and Callot, 1974).

For longitudinal dunes, the predominant wind directions are roughly parallel to the crest, though there remain two theories on the origin of this type of dune. Bagnold (1941) among others thought that seifs formed by the amalgamation and modification of barchans, under the influence of winds blowing predominantly from *two* directions (both in the same or adjoining quarters). Hanna (1969) has argued that longitudinal dunes in Australia and elsewhere are parallel to a single predominant wind direction, with sand blown up to the crest from the stony interdune areas by secondary currents. The secondary currents are supposedly spiral vortices whose scale is related to the thickness of the atmospheric boundary layers (about 1 km). On either theory, sand is blown across the crest, first from one side then from another, and McKee and Tibbitts (1964) found that, near the surface, a Libyan seif dune was composed of large-scale cross-strata dipping at high angles in two nearly opposite directions, each roughly normal to the dune crest. It appears, however, that longitudinal dunes are relatively stable types (many show a considerable degree of vegetation, except near the crest) which form in areas of only sparse sand supply: they grow at the downwind end and do not migrate laterally. It is therefore possible that the structures recorded by trenching near the crest are not typical of those, more likely to be preserved, in the deeper parts of the dune.

For whatever reason, there have been very few examples of longitudinal dunes identified in the geological record. Most ancient eolian sandstones are characterized by large scale, high angle (20 to 30°) cross-beds with a single prominent modal direction of dip and a range of about 90 degrees on either side of the mode. These sands, if in fact they are eolian, are generally thought to be deposited from transverse dunes.

Modern transverse dunes are of several different types. Isolated transverse dunes (barchans) are by far the simplest and clearest type; they are crescent-shaped dunes, with the "horns" pointing downwind. McKee's (1966) trenches of a barchan dune showed high angle cross-strata inclined downwind with a rather low spread of directions, and cut by numerous, low angle, erosion surfaces, inclined at low angles downwind. This is perhaps not what was previously expected, but in any event, it is unlikely that thick ancient deposits of eolian sand can have been deposited from barchans, because barchans form mainly in peripheral regions of ergs, where sand supply is very limited. Transverse dunes with more or less continuous crests oriented almost normal to the wind direction are also found in modern deserts. The internal structures of one example, about 12 m high, was investigated by McKee at White Sands. Thick sets of tabular, planar cross-beds were revealed, with closely spaced erosion surfaces near the top of the dunes, but with erosional surfaces widely spaced and dipping at moderate angles downwind in the lower part of the dune. This dune did not display the wedge shaped sets typical of some supposed ancient dunes. Wedge shaped sets were shown by parabolic (partly vegetated) dunes at White Sands. Parabolic dunes are more typical of vegetated coastal dunes than of modern desert dunes, but it seems probable that the wedge shape of the dune results more from the irregular, sinuous shape of the crest (which is certainly typical of many modern transverse dunes in deserts) than from any inherent property of the parabolic dune shape.

Up to the present time, the closest matching of a modern dune type with an ancient dune sandstone has been achieved by Thompson (1969). He has described well-exposed, large scale cross-bedding at four localities in the Triassic of Cheshire (England) which closely matches the cross-bedding described by McKee from dome-shaped dunes at White Sands. The dome shaped dunes described by McKee are relatively low types, only a few metres high, without active slip faces: they are thought to develop from transverse dunes in areas where dunes are exposed to strong winds which the dune can grow.

The structures formed in large, complex pyramidal dunes (which are surely the most likely to be preserved in the stratigraphic column) are almost completely unknown from direct investigation. It is generally assumed that, because of their complex morphology, the direction of dip of cross-bedding within these complexes must be equally disperse. A study of the Kelso Dunes in the Mojave Desert, California (Sharp, 1966) suggests that perhaps this is not necessarily the case. These dunes occupy an area of about 115 km^2 and rise to a height of 200 m above the surrounding land surface. The dune morphology is complex with transverse dunes superimposed on larger, oblique sand ridges: the wind regime is also complex, but predominantly from the west. Net changes in the positions of dunes measured over a 10 year period were small (50-100 m), despite highly active crestal movement related to short term changes in wind direction. Measurement of lee slope orientation at any one time showed a highly dispersed pattern, but trenching and more careful observation suggested that this was only a superficial phenomenon: cross-bedding observed in areas of reversed (westward dipping) lee slope was still predominantly eastward, and when an attempt was made to separate predominant from subordiante lee slopes the orientations corresponded fairly well with the predominant wind towards the east. Thus possibly the apparently chaotic form of draas is not representative of their internal structures. Many draas are found in regions where there is one predominant wind direction. Most sand is moved during relative short periods of strong winds (for a good description of a typical sand storm at White Sands, see McKee and Douglass, 1971), and it is possible that the cross-bedding reflects the orientations of these winds much more faithfully than does the large scale external morphology.

A feature of many ancient sandstones interpreted as eolian is the presence of near-horizontal surfaces that truncate sets of cross-beds and are generally spaced about 0.5 to 15 m apart. Stokes (1968) interpreted these surfaces as due to deflation of sand above a horizontal water table. McKee and Moiola (1975) recorded similar surfaces from interdune areas at White Sands, but pointed out that the water table in dunes is not generally horizontal (this objection does not seem entirely convincing, because progressive removal of sand from dunes would surely lead to the water table gradually approaching horizontality). They suggested that a water-table mechanism was not necessary, and that truncation surfaces are simply produced by dune migration. Brookfield (1977) has recently reviewed the occurrence and origin of bounding surfaces in eolian sands. He agrees that such surfaces are formed by the migration of large bed forms: the mechanism is basically the same as that which produces bounding surfaces between cross-bed sets in "normal" medium scale, water-laid cross-beds. Generally the spacing between such surfaces is only a fraction of the total height of the bed form. In eolian sandstones, this fact together with the known small rates of supply of wind-blown sand, implies that bounding surfaces spaced a few metres apart can only be formed by very large bed forms that migrate only very slowly, that is by the migration of draas.

Characteristics of Ancient Eolian Deposits

In constructing facies models for submarine fans, fluvial systems and deltas in earlier papers in this series, there was little doubt that, for instance, the ancient examples used to build the fluvial model were in fact fluvial in origin. Because of the current controversy about some of the "classic" ancient eolian units, and their possible shallow marine origin, it is not so certain that the eolian facies model is being constructed exclusively with eolian examples. We do not agree with the shallow marine reinterpretations, but will discuss this problem below. Our description is based principally on the "classic" eolian units of the southwestern U.S.A. listed in Table I.

Table I

Characteristics of classic ancient eolian sandstones of the Western United States

Formation	Age	Approx. Max Thickness (m)	Thickness of Cross-bed Sets	Dip of Cross-beds (degrees)	Type of Cross-bedding	Reference
CASPER	Penn.-Perm.	240	min. 15 m	15-25	mostly troughs	Steidtmann, 1974
COCONINO	Perm.	330	"huge"	25-30	randomly oriented wedge-shaped sets	Baars, 1962
CEDAR MESA	Perm.	450	up to 30 m	up to 25 sweeping toe-sets	mostly planar tabular	Baars, 1962
DE CHELLY	Perm.	330	up to 35 m	15-35	simple planar tabular sets	Baars, 1962
WHITE RIM	Perm.	200	up to 20 m	19-27 long toe-sets	mostly planar tabular	Baars & Seager, 1970
LYONS	Perm.	40	up to 13 m	commonly 25 max. 28	mostly planar tabular	Walker & Harms, 1972
WINGATE	U. Triassic	130	up to 15 m	up to 30		Dane, 1935
NAVAJO	L. Jurassic	700	up to 30 m	20-30 long toe-sets	lower part - mostly planar tabular sets normally 3-10 m upper part - most troughs. Sets normally up to 6 m	Sanderson, 1974; Freeman & Vischer, 1975
ENTRADA (Slick Rock Member)	U. Jurassic	280	up to 8 m		"wedging sets" "sweeping eolian cross-beds"	Craig & Shawe, 1975

Ubiquitous large scale cross-bedding

The major feature of all these units is the presence of extremely large-scale cross-bedding (Fig. 2 and Fig. 3). In fact, the scale and type of the cross-bedding ("sweeping", "wedging" sets) has become so identified with eolian deposition that authors feel they can refer to "obvious eolian cross-stratification" without any other description of the unit in question (e.g., Baars, 1975, p. 125).

Individual cross-bed sets in the units of Table I are up to 35 m thick. Commonly, many sets will be of this thickness, not just the exceptionally thick ones. Reading between the lines of the descriptions, it appears that there are two main types - planar-tabular (Cedar Mesa, De Chelly, White Rim, Lyons, Lower Navajo) and trough or wedge shaped (Casper, Coconino, Upper Navajo, Entrada). The exact

Figure 2

Single set of planar tabular cross bedding, at least 20 m thick from canyon floor to upper truncation surface. White Rim Sandstone (Permian, Utah).

Figure 3
Set of low angle cross bedding showing asymptotic passage of toesets into bottomsets. Note length and thickness of bottomsets: exposed thickness of set about 2m. White Rim Sandstone (Permian, Utah).

three-dimensional geometry of such immense sets is very hard to document, but there is probably a broad correlation between straight crested dunes and planar-tabular sets, and between sinuous crested dunes and trough or wedge-shaped sets.

One of the best descriptions of the detailed structure of the large cross-beds is that of Walker and Harms (1972; Fig. 4). In vertical cross section parallel to flow, the set appears to be planar-tabular. On the exhumed lee face, there are very low amplitude ripples that suggest sand was blown across the dune face. The plan view shows that the entire dune advanced down-dip *not* by sand avalanching down the lee face, but by the addition to the lee face of wedges of sand blown into place across the dune. These features have been illustrated in photographs by Walker and Harms (1972, their Figs. 1, 2, 6, 8), who also suggest that the foresets dip at an angle (25-28 degrees) less than that of the angle of repose of dry sand (about 34 degrees) because sand is blown along the face rather than avalanching over the dune crest.

Eolian trough cross-bedding has been described and illustrated by Knight (1929) from superb, three dimensional outcrops near Sand Creek, Wyoming. Knight's diagrams are now classic examples of symmetrical troughs, and still appear in text books to illustrate this feature. In the Casper Sandstone, these troughs are up to 305 m wide, several times as long, and at least 15 m deep. Excellent photographs are given by Steidtmann (1974).

Several authors make the observation that the large cross-beds commonly have very long, sweeping, asymptotic topsets and bottomsets (Fig. 3). These bottomsets appear to be longer, to aggrade into thicker units and to occur much more commonly in the units in Table I than in known subaqueous situations.

In summary, the outstanding feature of the cross-bedding is not only the immense scale (a few metres to a miximum of about 35 m), but also the fact that it occurs through great stratigraphic thicknesses (Table I) almost unrelieved by other lithologies or other sedimentary structures. This point will be discussed again later when controversial interpretations are considered.

Minor sedimentary structures. Many minor structures suggestive of subaerial deposition have been recorded from the eolian units listed in Table I. Some of the more important ones occur in the Lyons Sandstone (Walker and Harms, 1972), and include wind ripples, raindrop impressions, animal tracks, avalanche structures, and grain lag layers.

The ripples found in eolian units tend to be low, long wavelength features that may only be visible when sunlight glances across an outcrop. They are commonly oriented with crests parallel to the dip of foreset slopes (Fig. 4). A detailed view of the cross stratification in Figure 2 is shown in Figure 5. At about three levels, low angle cross lamination can be seen in sets each about one cm thick. This cross lamination is climbing *up* the main foreset slope, and is probably the stratigraphic record of small eolian ripples being blown diagonally up the foreset. By contrast, water-formed ripples of both wave and current type have lower ripple indices (wavelength/height), and are rarely oriented in the manner shown in Figure 4.

Animal tracks have been observed in many of the formations listed in Table I. Excellent examples are figured by Walker and Harms (1972, Fig. 12), who

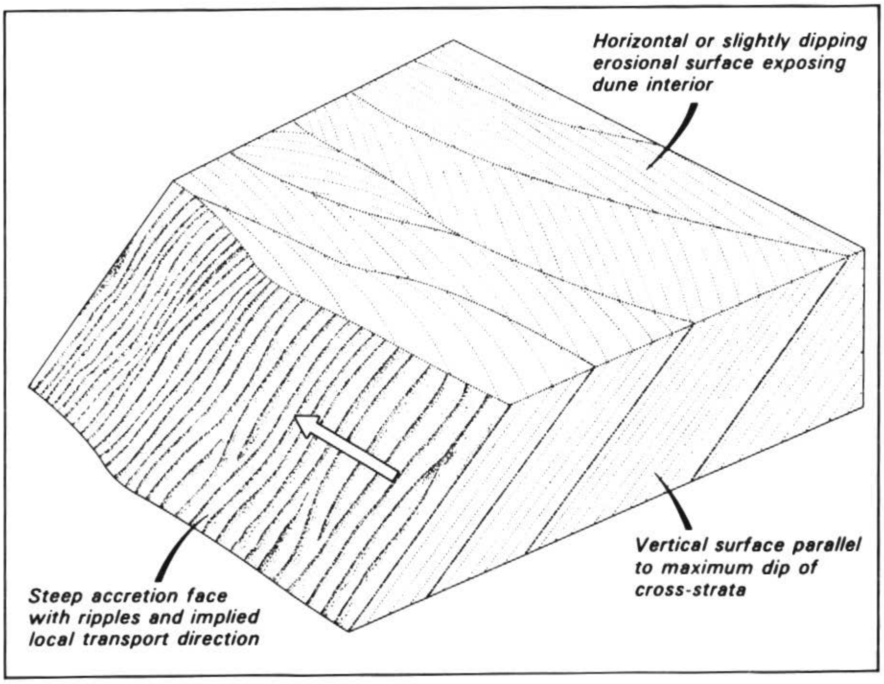

Figure 4
Geometry of eolian cross-bedding as seen in the Lyons Sandstone, Lyons Quarry (Permian, Colorado). From Walker and Harms (1972).

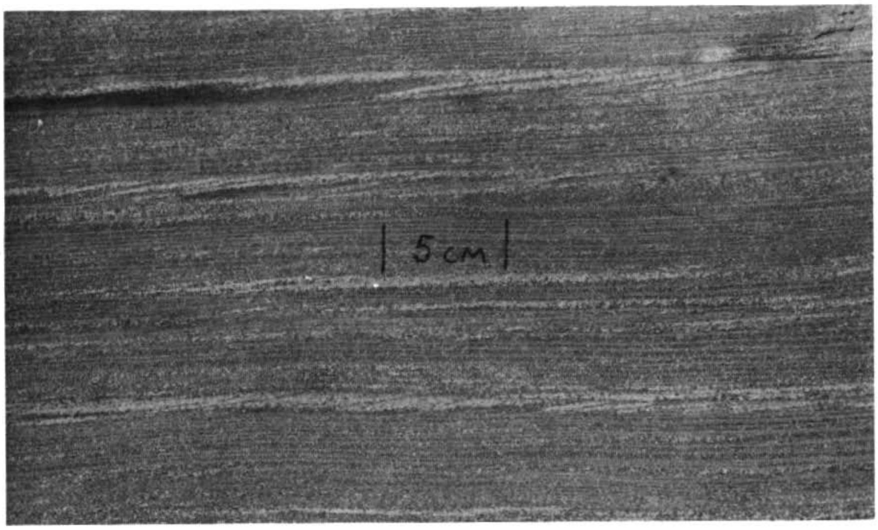

Figure 5
Detail of stratification on large foreset shown in Figure 2. Note the three thin sets of very low angle foresets, interpreted as low amplitude-long wavelength wind ripples, with sand being blown up the large foresets in Figure 2. White Rim Sandstone (Permian, Utah).

discuss experimental work indicating an exclusively subaerial, dry sand environment for the preservation of animal tracks.

Soft sediment deformation, in some cases on a very large scale (e.g., Sanderson, 1974) is known from several ancient eolian formations. Minor deformation structures have been described from modern dunes (see Bigarella, 1972). Many deformation structures seem to have been formed after sands become saturated with water, and therefore are not diagnostic of eolian deposition. There is one minor type, however, which does seem to be formed only in *partially* wet sands: small scale soft sediment faulting, (e.g., Steidtman, 1974), and this is found, for example, in the Navajo Sandstone.

Coarse lag deposits are known in modern interdune blowout areas (Bagnold, 1941, his Figs. 10, 53), and have also been described from the Lyons Sandstone (Walker and Harms, 1972, their Figs. 15, 16). The lags consist of coarser sand or gravel, and are characterized by very equal spacing of the grains on the lag surface. The equal spacing is a response to the dispersion of the larger grains in the lag bombardment from saltating sand blowing across the surface.

Within many eolian sandstones, there are thin mudstone, limestone or dolomite horizons representing the deposits of ephemeral lakes. The upper surfaces are commonly covered in desiccation cracks, ripple marks, and wavy laminae indicative of drying out. In the Navajo Sandstone, these thin fine grained layers are less than a few metres thick, and rarely extend for more than a square kilometre (Freeman and Visher, 1975, p. 661).

Paleontological evidence. The eolian units in Table I are characterized by a variety of dinosaurs, dinosaur tracks, fresh water ostracods, and plant remains. A summary of the Navajo and Nugget fossil occurrences has been given by Picard (1977). No marine fossils have been found within the main, large scale cross-bedded portions of these formations, although some of them intertongue with other marine formations (e.g., the Navajo intertongues in its upper part with marine limestones of the Carmel Formation).

Interpretation of Eolian Sandstones

Until about 1960, the units listed in Table I were widely accepted as being eolian in origin. The interpretations were based essentially upon four criteria: 1) the absence of a marine fauna, and presence of dinosaur bones, dinosaur tracks, and non-marine ostracods, 2) the similarity of the giant cross-bed sets to those found in modern dunes, 3) the abundance of giant cross-bed sets, and their monotonous occurrence through tens or hundreds of metres of section, 4) associated minor features, e.g., "wind" ripples, raindrop impressions, mud-cracked limestones and mudstone horizons. Criticisms of the eolian interpretation were published by Baars (1962, p. 178, Cedar Mesa) and Baars and Seager (1970, White Rim), who based their arguments on the style of the cross-bedding. Thus the Cedar Mesa was interpreted as "littoral to beach", citing "moderate to low angle cross-stratification, very low angle to horizontal thin sand beds, long sweeping curves from moderately dipping cross strata into horizontal fore-set beds, thin simple sets of low angle cross strata..." (Baars, 1962, p. 178). These features can equally well be interpreted as the long, low fore-sets and toe-sets of eolian dunes, the low angles being due partly to non-preservation of the steeper, higher parts of the dunes, and partly to the fact that the fore-set and toe-set was constructed by sand being blown around the dune, and over the dune crest in suspension, rather than avalanching. Baars did not mention, nor attempt to account for, the sets up to 30 m thick, which are unknown in modern littoral and beach environments. Criticism of the interpretation of the White Rim Sandstone (Baars and Seager, 1970) was based upon an irregular bar-like topography on the top of the White Rim. This bar like topography is mantled by a veneer of sand that is wave rippled, almost certainly in a marine environment. Baars and Seager (1970, their Fig. 6) show one veneered bar 1 to 3 km wide, about 15 km long, and with a vertical relief of 15 to 60 m. However, they base their interpretation of the White Rim Sandstone less on the immense cross-bedding within the White Rim (up to 20 m; Fig. 1), than on the eroded topography, the veneer, and the wave ripples *above* the White Rim.

Further criticism of the eolian origin of some of the units in Table I has been based upon comparisons with modern sand waves and tidal sand ridges that are common on many shelf areas (Houbolt, 1968; McCave, 1971; Swift, 1975). Thus Stanley, Jordan and Dott (1971, p. 13) wrote that "it can no longer be assumed *a priori* that large festoon cross strata prove an eolian dune origin for the Navajo or any similar sandstone *because of the essential identity of form and scale of modern submarine dunes or sand waves,* as documented during the last decade (e.g., Jordan, 1962)" (our italics). It is important, therefore that we describe briefly what the scale and form of these features is. We believe that some authors have misinterpreted the marine sand waves and tidal ridges, and hence have mistakenly reinterpreted some of the "classic eolian" units as shallow marine.

Marine Sand Waves and Tidal Ridges

These features have been described in detail from the North Sea (Stride, 1963; Houbolt, 1968; McCave, 1971) and the Atlantic Shelf off New England (Jordan, 1962.; Swift,1975). Houbolt's map of the tidal sand ridges shows that they may be 30 to 40 m high, about one to two km wide and 20 to 60 km long. More importantly, Houbolt made sparker sections across two of the ridges (Fig. 6) showing that they are asymmetrical, with a steep face toward the northeast, and apparent steep stratification surfaces within the sand ridges. However, it is clear in Figure 6 that the vertical scale on these diagrams is exaggerated, and calculation shows that the dip of the "steep" face averages only 5 *degrees.* Thus Houbolt's sand ridges are *not* modern examples of cross-bed sets tens of metres thick with dips of 5 to 30 degrees (Table I), and Houbolt does *not* "show cross stratification in the submarine sand ridges of the North Sea to exceed 40 m in thickness" (as claimed by Pryor, 1971, in a reinterpretation of the "classical eolian" Permian Weissliegendes Sandstones of Germany).

Similar problems exist if tidal sand waves are used as a basis for interpretation. Sand waves have been described in the North Sea by McCave (1971) and Terwindt (1971). They are up to seven m high, with wavelengths of 200 to 500 m. McCave's echo soundings (Fig. 7) show that they have asymmetrical profiles, but calculations show average dips of 5 degrees on the "steep" face. Terwindt (1971, his Table 1) gives value for slopes on the sand waves in 21 locations, and the maximum steep face angle is only about 11 degrees. The mean steep face angle, calculated from Terwindt's table, is 4.5 degrees. Thus despite their height and asymmetry, tidal sand waves of this type are clearly unsuitable models for the reinterpretation of "eolian cross-bedding", despite the brief comment of Stanley, Jordan and Dott (1971) cited earlier, and the more detailed reinterpretation of the Navajo by Freeman and Visher (1975).

The sand waves described by Jordan (1962) from Georges Bank (Gulf of Maine) are probably the largest and steepest reported. On Georges Shoal, the sand waves are up to 13 m high but are mostly symmetrical with calculated dips of "steep" faces of about 2 to 3 degrees. On Cultivator Shoal, the sand waves are asymmetrical, up to about 10 m high with steep faces of about 18 to 20 degrees. In most studies (Houbolt, 1968; McCave, 1971), the sand waves and tidal ridges appear to be covered with small bedforms (megaripples) - their migration would produce cross-bedding of a scale up to about a metre and the probable internal structure of the sand waves and tidal ridges would be complex, medium scale cross-bedding (with sets less than 1 m thick). Due to regular reversal of tidal currents, and the fact that different sides of tidal ridges are generally dominated by different phases (flood or ebb) of the tide, at least some of the cross-beds should be dipping almost opposite directions. One would expect to see abundant internal truncations ("reactivation surfaces") and at least some "herringbone" or bipolar cross-bedding.

The low angle of the "steep" faces of tidal sand ridges and sand waves (commonly about 5 degrees) makes a shallow marine reinterpretation of the units in Table I unlikely. Even if

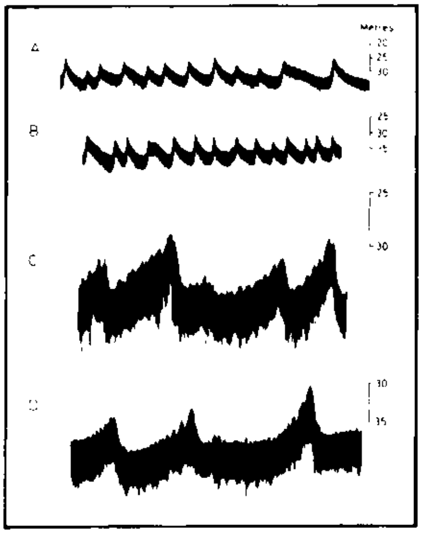

Figure 7
Profiles of sand waves in the southern bight of the North Sea. Vertical scale positioned with respect to sea level = 0 m. Lengths of sections about 3800 m (A); 2800 m (B); 900 m (C); and 1220 m (D); Calculated dips of "steep" faces average 5 degrees. (From McCave, 1971, p. 206)

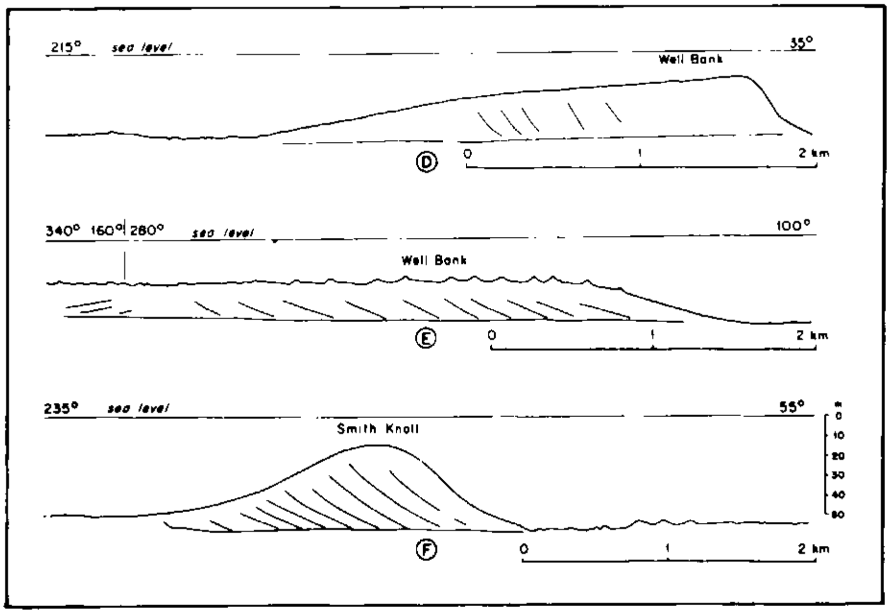

Figure 6
Sparker profiles of tidal sand ridges off southeast England. Although they look like asymmetrical cross-bedded features, compare the vertical and horizontal scales given. Calculated "steep" slopes average only 5 to 6 degrees. (From Houbolt, 1968).

comparison were made with Cultivator Shoal (heights up to 10 m, dips 18 to 20 degrees) the scale is still too small. However, we consider the other evidence to be overwhelmingly in favour of the classic eolian interpretations, namely the scale, abundance and monotony of the immense cross-bedding through tens or hundreds of metres of section, the absence of marine faunas, and the strong indicators of subaerial deposition - dinosaur tracks, raindrop impressions, gravel lags of equally-spaced grains, and interbedded thin mud-cracked layers. The latest marine reinterpretation of the Navajo (Freeman and Visher, 1975) has been positively and convincingly shot down by Picard (1977), Folk (1977), Steidtmann (1977) and Ruzyla (1977). Their arguments along with the excellent eolian documentation of the Lyons Sandstone by Walker and Harms (1972), constitute the most important pro-eolian literature.

Eolian Facies Model

In previous papers in this series, the facies models have been presented not only in terms of types of sedimentary structures, but in terms of their sequence and association. Examples include the fluvial fining-upward sequences and the deltaic coarsening-upward sequences. Based upon the sequences, it has been shown that the facies models can act as a norm (for purposes of comparison), a predictor (in new situations) and a guide for future observations.

By contrast, in eolian systems, there seems to be no preferred vertical sequence of sedimentary structures, nor any consistent lateral changes. This may be due to insufficient study of sequence in ancient eolian sandstones, or a tendency for irregular and unpredictable distribution of dune types in a desert. The result is that the "eolian facies model" can only be stated in terms of an assemblage of characteristic features, which may act as a norm, and as a guide to future observations, but which cannot act successfully as a predictor in new situations.

The single most characteristic feature must still be the large sets of cross-bedding on a scale of 5 to 35 metres, not simply occurring singly, but in monotonous cosets tens or hundreds of metres thick. Other features that strengthen the interpretation are the stratigraphic context and absence of marine fossils in the sandstones, and the minor features that indicate subaerial deposition.

As a guide for future observations, we would stress the importance of hunting for the minor features such as raindrop impressions, soft-sand faults, and animal tracks, that (in conjunction with abundant large scale cross-bedding) indicate subaerial depositon. Eolian sandstones might be expected to be interbedded with, or intertongue with, fluvial and alluvial fan sediments (Laming, 1966), or to overlie coastal sediments in regressive sequences.

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