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Palaeoclimatic evidence from sand seas

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Abstract

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Sand seas can be an important source of information on the Quaternary history of many deserts. Because sand seas appear to react sensitively to climatic changes, the quality of palaeoenvironmental information obtained from them is frequently much better than that from adjacent rocky desert areas.

Patterns of dune alignments may be used to reconstruct the wind directions that formed currently inactive or fixed dunes and thus can provide information on palaeocirculation patterns. The climatic conditions under which these dunes formed can be examined using palaeoclimatic models to explore the combinations of wind velocity, rainfall and evaporation rates required to reactivate them. Choice of appropriate values for these parameters may be hampered by the problems of dating episodes of dune activity.

In many sand seas, the best palaeoclimatic information comes from studies of interdune lacustrine or playa deposits, which may reflect increased local rainfall or higher groundwater discharge, or greater penetration of the sand sea by rivers with headwaters outside the desert. Caution should be taken in the interpretation of such deposits, for juxtaposition of aquatic and aeolian environments can occur even in modern hyperarid sand seas.

The record of climatic changes preserved in the deposits of modern sand seas suggests that periods of dune formation may have been interrupted by long periods of stability, which may also have included deposition of interdune lacustrine deposits. For example, within the past 40,000 years, active dune formation in many sand seas appears to have been restricted to the interval between about 20,000 and 12,000 yr B.P., and to the late Holocene (approximately 1/4 to 1/3rd of the time).

Introduction

Sand seas are an important component of the landscape in many old world sub-tropical desert regions. Major areas of sand sea accumulation occur in the Sahara, Arabia, central Asia, Australia and southern Africa (Fig.1), where dunes cover between 20 and 45% of the area classified as arid (Table I). In many of these areas, aeolian deposits make up a significant percentage of the Quaternary sediments, so in order to understand the Quaternary history of such regions it is necessary to study the history of the accumulation of the sand seas. There is also evidence, in the form of dune systems now stabilized or fixed by vegetation (Fig.1) that many sub-tropical sand seas were much more extensive in glacial periods (e.g. Grove and Warren, 1968; Bowler, 1976; Sarnthein, 1978; Thomas and Goudie, 1984). Such fixed dune systems can provide valuable information on palaeowinds and circulation patterns.

Sand seas can provide palaeoenvironmental information from three main sources: (1) dune systems, especially those fixed by vegetation; (2) interdune deposits; and (3) penetration of extra-dune fluvial deposits into the margins of the sand sea. The quality of palaeoclimatic data provided from sand seas is frequently much better than that obtained from adjacent rocky desert regions, as sand dune areas tend

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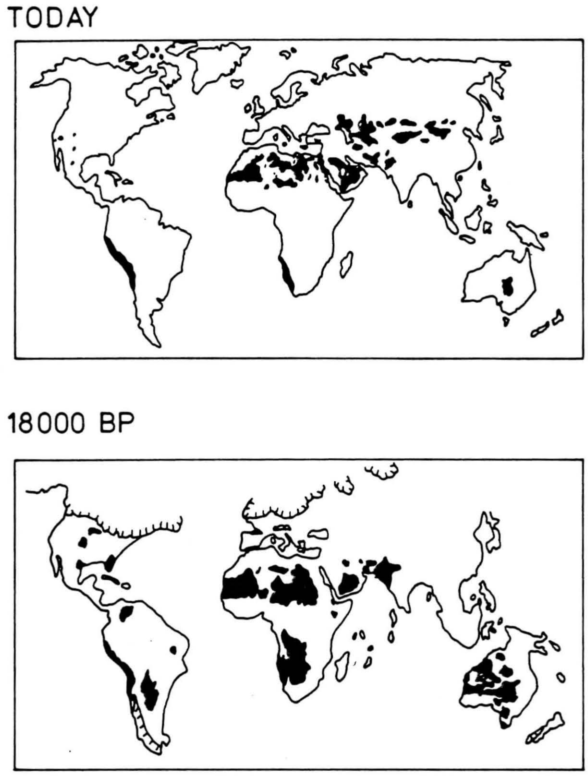

Fig.1. Extent of active desert sand seas today and at 18,000 yr B.P. (after Sarnthein, 1978).

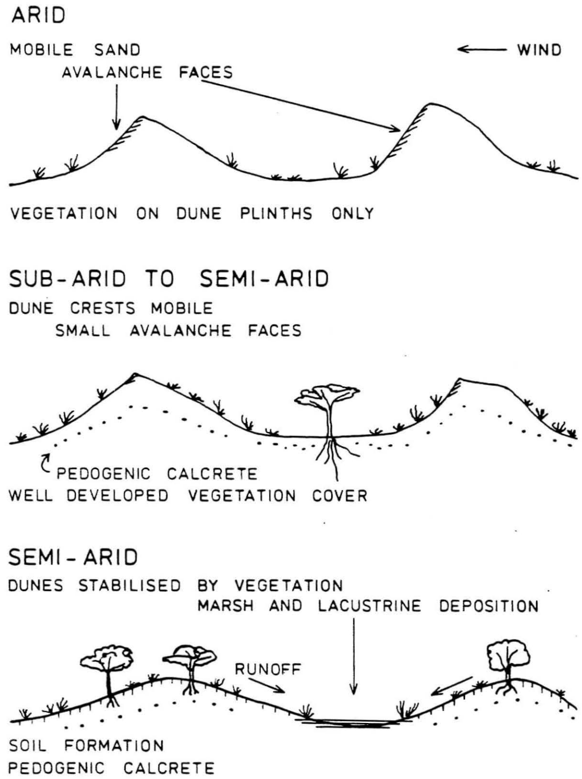

Fig.2. Reaction of sand seas to climatic change (after Rognon, 1982).

TABLE I

Percent of area covered by dunes in major desert areas (data from Breed et al., 1979)

South West USA	0.6
Sahara	28.0
Arabia	26.0
Australia	31.0
Southern Africa	16.0
Central Asia	4.5
China	3.6

to accentuate the effects of both dry and wet phases (Rognon, 1982). In periods of increased rainfall, the high infiltration capacity and porosity of dune sands favors the growth and persistence of vegetation, which may lead to the partial or complete stabilization of the dunes, and formation of soils in dune sands (Fig.2). If the periods of increased rainfall are of sufficient magnitude and duration, then water tables will rise, leading to the accumulation of pond and marsh deposits in interdune areas. In periods of intense rainfall, runoff may erode dunes (Talbot, 1985). In contrast, periods of aridity will give rise to a very unfavorable biotic environment within the sand sea, with low water tables and active sand movement preventing the growth of vegetation.

This paper reviews the nature of palaeoclimatic evidence that can be gained from sand seas, and discusses some of the problems of its interpretation. Tentative models for the effects of climatic change on sand sea development are suggested. The bias toward evidence from southern Africa reflects my experience in this region.

Dune systems

Dune systems, especially those that are stabilized by vegetation, can provide important palaeoenvironmental information on the former extent of aridity, and on palaeowinds and circulation patterns.

Former extent of arid climates

Mobile or active continental sand dunes exist today, where sand supply conditions permit, in areas where mean annual rainfall is 100–150 mm or less. The existence of such dunes has thus been regarded as an unequivocal index of arid climates. The distribution of fixed or vegetated dunes in areas where rainfall is above this limit provides evidence for the former extent of arid climates. Comparisons between the precipitation limits of active and fixed dunes may therefore indicate changes in the distribution and latitudinal position of arid climates.

Extensive systems of dunes, mostly fixed by savanna vegetation, have been recognised from the margins of modern active sand seas in the Sahel (e.g. Grove and Warren, 1968; Talbot, 1984), southern Africa (Lancaster, 1981; Thomas, 1984), India (Goudie et al., 1973) and Australia (Bowler, 1976; Wasson, 1984). They have been identified from aerial photographs and satellite images in areas with up to 1000 mm of annual precipitation, several hundred kilometers from the margin of areas of active dunes. Comparison of the precipitation limits of active and fixed dunes can provide an indication of the magnitude of changes in the position of climatic belts (Table II). This approach has proved useful in the Sahelian zone of western Africa (Fig.3), where there is a strong latitudinal pattern to climatic and vegetation zones. However, in the eastern Sahara, Australia and southern Africa, the evidence suggests that the area of aridity may have expanded and contracted about a central core region which has always remained arid (Haynes, 1982; Lancaster, 1984).

TABLE II

Precipitation limits of active and fossil dunes

	Active dunes (mm)	Fossil dunes (mm)	Implied isohyet shift (km)
Arizona	238–254	305–280	
Texas			350
NE Brazil			600
West Africa	150	750–1000	1000
Sudan			200–450
Zimbabwe		300	500
N Kalahari	150	500–700	1200
SW Kalahari	100	300–400	250
Australia	100		900
W Australia	200	1000	800
India	200–275	850	350

Changes in dune mobility

The formation or reactivation of areas of dunes may be the product of shifts in climatic belts and circulation patterns, but it is now

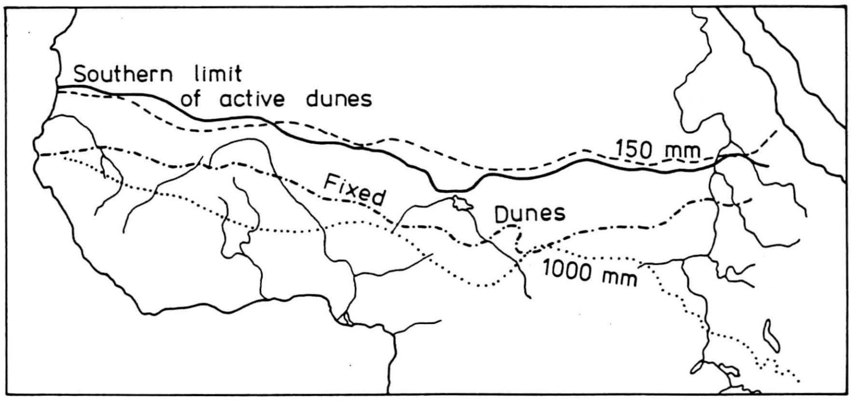

Fig.3. Latitudinal changes in equatorwards extent of active dunes in the Sahel zone of Africa.

clear that such models are over-simplified. The importance of interactions between wind velocity and vegetation cover (and hence rainfall) on sand mobility are now being increasingly recognised in Australia (Ash and Wasson, 1983), the Sahel (Talbot, 1984) and southern Africa (Lancaster, 1988). Reactivation or formation of dunes may be the result of changes in wind velocity and/or the moisture balance. These may occur without significant changes in the area of aridity. However, in some areas, decreases in sand supply as a result of changes in river sediment loads or exhaustion of sources of sand may reduce dune mobility to such an extent that vegetation cover increases and the dunes are effectively stabilized. This appears to be the case in many dunefields in the Mojave and Sonoran deserts of North America.

Changes in wind velocity and/or moisture balance

The mobility of desert dunes is directly proportional to the sand moving power of the wind, but inversely proportional to their vegetation cover (Ash and Wasson, 1983). In turn, vegetation cover is a function of the ratio between annual rainfall (P) and potential evapotranspiration (PE). An index of the sand moving power of the wind is the percentage of the time the wind is blowing above the threshold velocity for sand transport (4.5 m/s) (W). The ratio between these two terms gives a mobility index (Lancaster, 1988):

$$M = W/(P/PE)$$

In southern Africa, there is a gradient in sand mobility, as defined by this relationship, from the northern and eastern parts of the southwestern Kalahari to the active Namib Sand Sea (Fig.4), that accurately parallels observations of the amounts of sand movement on dunes in the region (Lancaster, 1988). Critical values for M, based on field observations of dunes, indicate that dunes are fully active when M exceeds 200; dune plinths and interdunes are stabilized when M lies between 100 and 200; dune crests only are active with M between 100 and 50; and dunes are completely stabilized when M is less than 50. It is clear from Fig.4 that significant increases in wind velocity or changes in the moisture balance must have occurred during periods when the dunes in the southwestern Kalahari were formed or remobilized.

The palaeoclimatic record for the southwestern Kalahari (Lancaster, 1989) suggests that the dunes were potentially active in the period 19,000–16,000 yr B.P., coeval with the last glacial maximum in high latitudes. During this period in southern Africa, mean annual

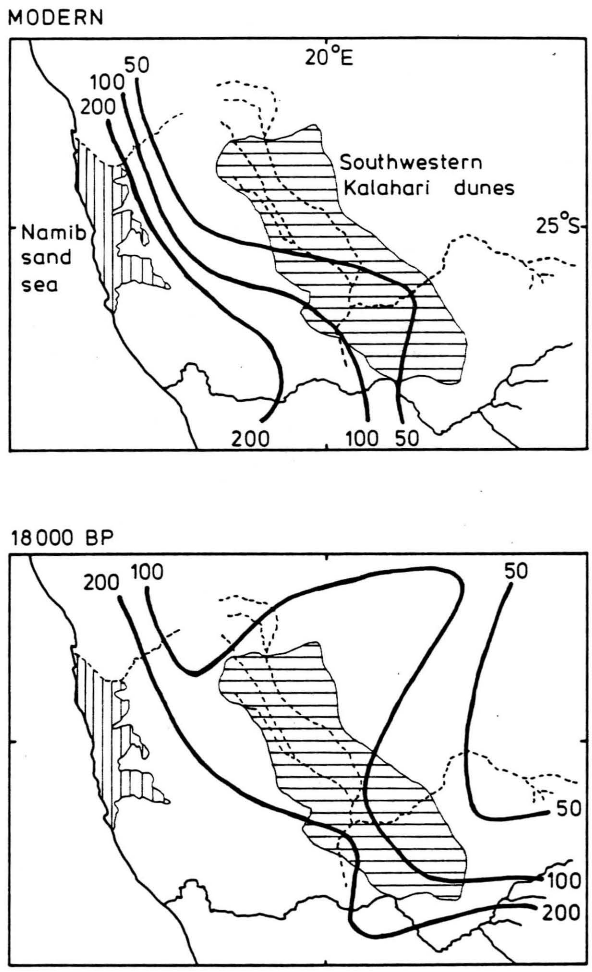

Fig.4. Spatial variations in potential dune mobility in southern Africa, as expressed by the mobility index (M), today and at 18,000 yr B.P.

temperatures were some 5°C colder than at present (Heaton et al., 1986). Newell et al. (1982) indicate that wind velocities at the latitude of the southwestern Kalahari would have been 117% of present values during this period. An increase in wind velocity of this magnitude would have been sufficient to substantially increase the sand-moving power of winds in the region, giving rise to an increase in *W* from its present mean value of 17% to 37%. Although *PE* would have been reduced as a result of lower temperature, the increased windiness in the region would have been sufficient to reactivate dunes over most of the southern and western parts of the sand sea (Fig.4). However, to reactivate dunes in the northern and eastern parts of the southwestern Kalahari, changes in the moisture balance, involving a reduction in mean annual rainfall of 30–40%, would have also been necessary.

In the Sahel, Talbot (1984) concluded that, despite an increase in late Pleistocene wind velocities of 50%, dune formation and re-activation in the period 25,000 or 20,000–13,000 yr B.P. would have required a reduction in rainfall to 25–50% present values. However, Ash and Wasson (1983) suggested that an increase in wind velocity of 20–30% would result in the mobilization of Simpson Desert linear dunes. Wasson (1984) argued that increased windiness during the late Pleistocene dune building phase (20–13,000 yr B.P.) would have increased *PE* and enhanced aridity, even without any reduction in rainfall.

These variations in the palaeoclimates inferred for episodes of dune formation probably reflect regional differences in the limiting factor (wind speed or vegetation cover) that controls dune activity. More sophisticated modelling of the conditions for dune formation is required, especially from areas such as the southwestern U.S.A. where it is possible to constrain some of the climatic variables by using palaeobotanical evidence for former temperature and precipitation conditions.

Changes in sand supply

Many sand seas are fed by material deflated from areas of marine, fluvial or lacustrine sands. High deflation rates are dependent upon active re-supply of the source areas. There is thus a close link between dune activity and the supply of sediment. Dune formation may thus be favored in periods of geomorphic instability and enhanced fluvial sediment loads. This appears to have been the case in the Mojave Desert (Wells et al., 1987) and Australia (Wasson, 1984).

In the Gran Desierto of Mexico, tectonic activity and changes in the course and sediment load of the Colorado River during the Pleistocene have resulted in three relatively brief periods of eolian deposition evidenced by three populations of mineralogically and texturally distinct sands. These periods of input and deposition of aeolian sand were separated by long intervals of geomorphic stability during which localized reworking of dunes occurred, leading to the modification of crescentic dunes to star and other complex dunes. The low rates of sediment generation and transport in the modern Gran Desierto suggest that it is in a period of relative geomorphic stability, a situation that has probably existed during much of the late Holocene (Blount and Lancaster, 1989).

Eustatic changes in sea level may have a important effect on sand supply. Littoral sands exposed during Glacial low-stands provided a ready source for sand seas in the Arabian Gulf (Shinn, 1973), the Namib (Lancaster, 1982a), southern Australia (Sprigg, 1979), and the Gran Desierto (Blount and Lancaster, 1989). Elsewhere, dunes prograded across exposed shelf areas in northwestern Africa (Sarnthein and Diester-Haas, 1977); and northwest Australia (Jennings, 1975).

Palaeowinds and circulation patterns

Comparisons between the modern pattern of sand-moving winds and dune alignments may provide important information on palaeocirculation patterns. In some areas of fixed dunes, the alignments of the dunes depart significantly from the direction of modern sand-moving winds, indicating that when the dunes were formed, wind regimes differed from those found today (e.g. Breed et al., 1979). Such conclusions are only valid if there is a good knowledge of the characteristics of the modern wind regime; and if the relationship between dune alignments and winds is known from studies of active dunes.

In the Kalahari region of southern Africa, Lancaster (1981) and Thomas (1984) have recognised three systems of fixed dunes, each corresponding to a different palaeowind pattern. Patterns of winds for all periods of dune formation (Fig.5) suggest that periods of aridity and dune formation in southern Africa were associated with, and probably caused by, increased persistence and strength of anticyclonic circulations, which also prevented moisture-bearing winds from reaching the interior of the sub-continent.

Modern annual resultant potential sand flows approximately parallel the dunes in the southern part of the southwestern Kalahari sand sea (Fryberger, 1979; Lancaster, 1988), whereas in northern areas, annual resultants of potential sand flow cross the dunes at angles of 60–90° (Fig.6). Linear dunes extend approximately parallel to the resultant direction of sand transporting winds (Lancaster, 1982b), and it is clear that formation of dunes in these parts of the sand sea took place in a wind regime unlike that of today. The pattern of alignments of the southwestern Kalahari dunes reflects the interaction of circulations around both the South African and South

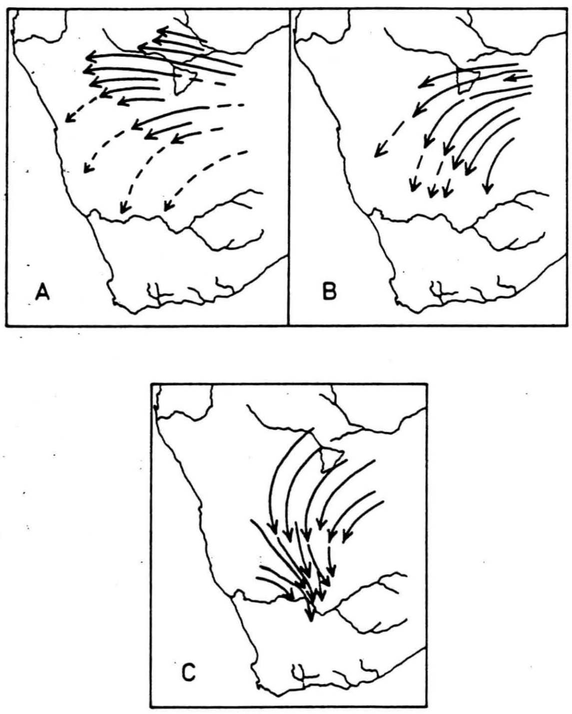

Fig.5. Patterns of winds inferred from the alignments of fixed dune systems in southern Africa (after Lancaster, 1981).

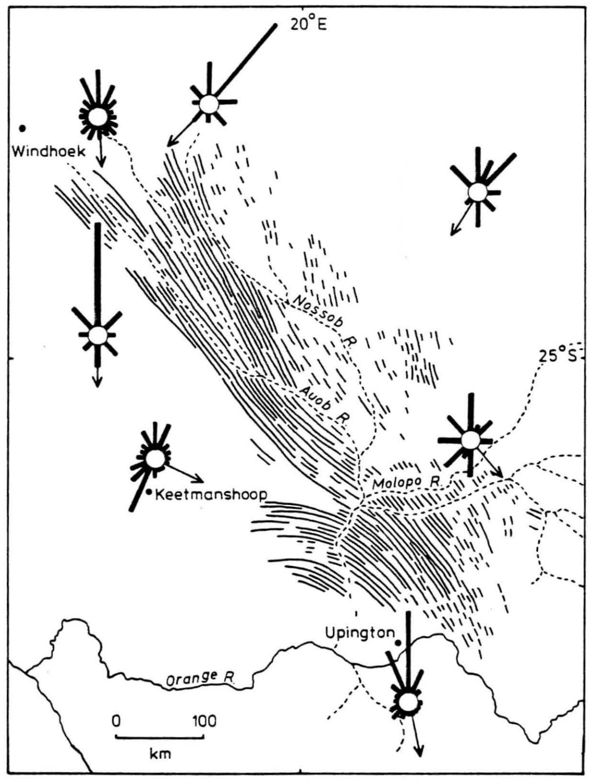

Fig.6. Pattern of linear dunes derived from Landsat images, and potential sand transport by modern winds in the southwestern Kalahari region. Rose diagrams show percentage of annual potential sand transport from each wind direction and direction of annual resultant sand transport (from Lancaster, 1981).

Atlantic anticyclones (Lancaster, 1981). The dunes were formed by resultant sand transport from the NW or WNW. In winter, when the South African anticyclone is at its most intense, winds in the region are dominantly northerly or northeasterly and all potential sand transport vectors cross the dunes, often at 90°. However, in September and October, when the relative strengths of the two anticyclonic circulations are comparable and winds are also at their strongest, resultant sandflows throughout the region are from the NW or WNW, or parallel to the dunes (Fig.7). It appears that, when the dunes of the southwestern Kalahari were formed, circulation patterns over the year closely resembled the modern October pattern, a situation that often applies in modern drought years. This suggests that periods of dune formation in the region were associated with strongly anticyclonic circulations and increased regional pressure gradients.

In North America, Wells (1983) compared modern winds and the alignments of dunes formed during a late Glacial period of aeolian activity that peaked 14,000 yr B.P., and inferred a shift in wind directions of 40–90° toward the north. The change in wind directions was especially marked in the southern Great Plains, and least in the desert regions of the Southwest. Wells (1983) attributed the changed wind regime to the development of three Rossby waves at latitudes 40–50°N, whereas the modern circulation typically displays a 4 or 5 wave pattern.

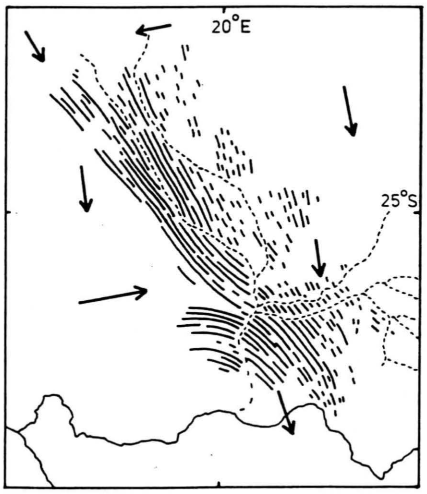

Fig.7. Southwestern Kalahari linear dune alignment pattern and modern resultant sand transport direction in September–October. Note close correspondence in southern part of region, but divergence in north.

In Australia, linear dune alignments parallel modern resultant sand transport directions in northern and eastern parts of the arid zone (Bowler and Wasson, 1984). However, in the southern Strzelecki desert, and the semi-arid Mallee area, dune alignments are W–E, but modern winds are from the southwest (Sprigg, 1979, 1982; Bowler and Wasson, 1984). Increased frequency of summer west and northwest winds during the period of dune formation 20,000–12,000 yr B.P. was attributed by Bowler and Wasson (1984) to steeper pressure gradients around the anticyclonic belts and more frequent passage of fronts to the south of the continent.

Interdune deposits

The extent and significance of interdune deposits in modern sand seas is being increasingly recognised (e.g. Ahlbrandt and Fryberger, 1981; Lancaster and Teller, 1988). Such deposits may be formed by lacustrine, fluvial, or evaporitic processes. Interdune lacustrine deposits and their associated fossil faunas can provide data on the extent and nature of humid conditions within and adjacent to the sand sea; and the chronology of sand sea accumulation through radiometric dating and studies of archaeological material. Interdune deposits that formed as the result of the penetration of extra-dune fluvial environments into the sand sea can provide data on humid conditions in headwater regions adjacent to the sand sea, as well as the development of dune patterns.

In the Namib Sand Sea, interdune lacustrine deposits of restricted extent have been laid down periodically during the accumulation of the sand sea (Fig.8). These carbonate-rich deposits are indicative of increased moisture availability in this normally hyper-arid to arid

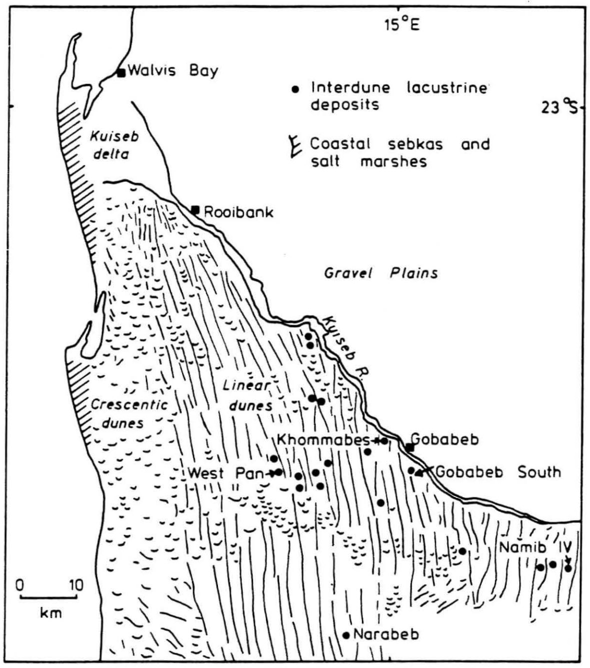

Fig.8. The northern Namib Sand Sea, showing location of major interdune lacustrine carbonate deposits.

region. Diatom and molluscan faunas indicate that the water bodies were fresh to brackish in composition (Teller et al., 1988). Modern analogues suggest several possible depositional environments. Shallow seasonal or ephemeral lakes may have formed in interdune areas as a result of increased regional or local precipitation. Long-continued periods of increased rainfall may have raised local groundwater levels such that seepage from shallow aquifers occurred. In some areas, such as at Khommabes on the northern margin of the Sand Sea adjacent to the Kuiseb River, lakes may have formed adjacent to ephemeral water courses in response to high groundwater levels in those river valleys (Teller and Lancaster, 1986a). At other localities, for example at Narabeb, lakes formed at the former end points of ephemeral rivers, which at one time were able to penetrate much farther west into the Sand Sea than they do now (Seely and Sandelowsky, 1974; Teller and Lancaster, 1986b). This implies that rainfall and runoff in the headwaters of the rivers in the highlands east of the Sand Sea were at times greater and/or that linear dune patterns were sufficiently open to permit water to flow as much as 40 km west of the present terminal playas of these rivers. Radiocarbon dates on many of the interdune lacustrine carbonates and molluscs cluster between 20,000 and 32,000 yr B.P. (Vogel and Visser, 1981; Lancaster and Teller, 1988). Evidence from elsewhere in the arid zone of southern Africa (Heine, 1982; Deacon and Lancaster, 1988) indicates that rainfall throughout this climatic zone was probably significantly higher during the period when these lacustrine beds were deposited.

In northern Saharan sand seas, increased flooding of the Wadi Saoura and lakes in the Chott Djerid basin also indicate increased moisture availability between 40,000 and 20,000 yr B.P. (Rognon, 1987). Similarly wet conditions occurred in the southern Sahara sand seas during the period 30,000–20,000 yr B.P. (Talbot, 1980; Fabre and Petit-Maire, 1988) and again in the Holocene between 9000 and 7000 yr B.P., when lacustrine conditions were very extensive (Rognon and Williams, 1977; Talbot, 1980; Fabre and Petit-Maire, 1988). Periods of increased moisture are indicated for the area of the Murzuq sand sea of Libya at 16,000–125,000, 90,000 and 22,500–26,000 yr B.P. (Petit-Maire et al., 1980). In the Great Sand Sea of western Egypt, Hayes (1982) reports periods of increased rainfall in the Middle Palaeolithic and Neolithic. The extent of the Neolithic "pluvial" is confirmed by pollen evidence that indicates permanent lakes surrouded by savanna woodland in the now hyperarid northwest Sudan between 8500 and 6100 yr B.P. (e.g. Haynes et al., 1979; Haynes and Mead, 1987; Ritchie et al., 1985), and by a variety of evidence for high lake levels throughout the southern Saharn margins (e.g. Street and Grove, 1979). In Saudi Arabia, interdune lacustrine deposits from the Nafud and Rub-al-Khali sand seas indicate moist conditions between 32,000 and 24,000 yr B.P. and again between 8500 and 5000 yr B.P. (Whitney et al., 1983).

Problems of palaeoclimatic inference from sand seas

A variety of evidence indicates that many sand seas have experienced significant climatic changes in the past 50,000 years. It appears that the period from 40,000–50,000 to 25,000–20,000 yr B.P. was a time of substantially increased moisture in many sub-tropical sand seas, whereas the interval between 20,000 and 12,000 yr B.P. was characterized by dune formation and/or reactivation in many areas. Some sand seas (notably in the southern Sahara) experienced a further period of humid conditions in the early Holocene. Despite these generalizations, it is rarely possible with present knowledge to say how wet conditions really were, or to characterize the boundary conditions for dune formation or reactivation.

Dating of arid episodes is frequently very difficult, and most inferences of aridity are made on the basis of the absence of evidence for humid conditions. True stratigraphic sequences of dunes and deposits indicative of humid conditions are rare. Where they do occur (e.g. the Great Sand Sea of Egypt) they indicate that periods of aridity and dune formation alternated with semiarid conditions when dunes were stabilized by vegetation, and playas and palaeosols formed in interdune areas (Haynes, 1982). This sequence covers the last 300,000 yr. However, precise dating of dunes and periods of aridity is hampered by the poor preservation of dateable evidence. Paleosols and charcoal are infrequently preserved in dune deposits of active sand seas. Thermoluminescence dating has been used to date dunes in India (e.g. Singhvi et al., 1982), and this technique has considerable promise for the future.

Interdune lacustrine deposits frequently provide the absolute data on which chronologies for periods of humid conditions can be developed. However, rapid deflation and poor preservation of these deposits limits their use in many sand seas. In the Namib, interdune lacustrine deposits are only preserved when they are protected by carbonate cement or indurated horizons, or rapidly buried by migrating dunes. Deflation rates of as much as 0.5–1.0 m/100 yr have been noted by Lancaster and Teller (1988).

In some sand seas, there is today a remarkable juxtaposition of depositional environments indicative of both humid and arid conditions. In the Namib, reed beds and springs that are fed by seepage from shallow aquifers occur next to active linear and crescentic dunes. River valleys provide "linear oases" that extend conditions indicative of the more humid highlands to the east far into hyper-arid sand seas (Ward et al., 1983). These modern environmental contrasts should be considered carefully in interpretations of palaeoclimatic evidence from sand seas, especially where there is reason to believe that groundwater discharge is important.

Discussion

Examination of the record of climatic changes preserved in the deposits of modern sand seas suggests that periods of dune formation may have been interrupted by long periods of stability, which may also have included deposition of interdune lacustrine deposits. For example, within the past 40,000 years, active dune formation in many sand seas appears to have been restricted to the interval between about 20,000 and 12,000 yr B.P., and to the late Holocene (approximately 1/4 to 1/3rd of the time). In the hyperarid cores of the old world deserts, periods of dune formation may have continued for much longer. Haynes (1982) and McHugh et al. (1988) indicate that aridity and dune formation have have been continuous from prior to 35,000 yr B.P. to around 10,000 yr B.P. Long, but discontinuous, records of human occupation based on lithic artefacts suggest that "pluvial" periods may have occurred in the eastern Sahara at intervals throughout the middle and late Pleistocene (e.g. Wendorf and Schild, 1980; McHugh et al., 1988). Such observations have considerable significance for interpretations of the rock record of aeolian sandstones, some of which (e.g. Permian Rotliegendes Sandstone of northwestern Europe) also accumulated at a time of high-latitude glacial conditions (Glennie, 1983).

The recent recognition of extensive, regional-scale super bounding surfaces between sets of aeolian cross-strata in a number of Permian to Jurassic aeolian sandstones in the western U.S.A. (Kocurek, 1988) implies that these thick sandstones accumulated not as a single long-lived sand body, but as a series of genetically independent sand seas of reltively short duration separated by long hiatuses when the dunes were partly or completely stabilized and planed off. This may have been the result of changes in climate (Talbot, 1985), sea level or tectonic setting, or the migration of the sand sea as a body (Kocurek, 1988). It is probable that the sedimentary record of modern desert sand seas reflects a similar pattern of episodic development, as originally suggested by Wilson (1971), with Quaternary climatic changes being a major influence on the rate and nature of their accumulation.

Figure 9 shows a possible model for the effect of climatic changes on sand seas. In periods of high rainfall dunes are stabilized by vegetation, and the sand sea is dormant. With a change to greater aridity, a pulse of aeolian sand input is generated by deflation of lacustrine and fluvial deposits laid down in the humid period, and by active sand supply from increased fluvial sediment yields resulting from geomorphic instability. This period is characterized by active aeolian deposition and rapid dune migration. As the sediment sources are exhausted, sand supply to the sand sea declines and active aeolian deposition is replaced by reworking of existing sediments and slow migration of existing dunes.

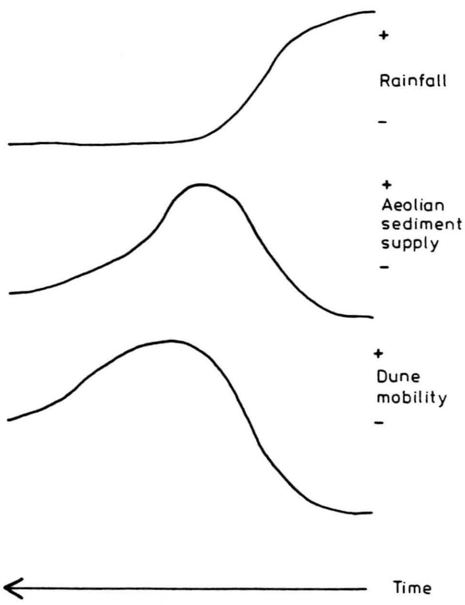

Fig.9. A model for the effects of climatic change on dune mobility and aeolian sedimentation in desert sand seas.

Conclusions

Desert sand seas have provided a considerable amount of information on Quaternary climatic changes in arid regions. Dunes provide some of the best evidence for past wind regimes and circulation patterns, and data from this source have an important input to global climatic models. Interdune deposits provide evidence that currently hyperarid regions were affected by considerably increased rainfall that stimulated the growth of vegetation and stabilized the adjacent dunes.

The effects of Quaternary climatic changes appear to have been most marked in the marginal areas of modern desert regions, where climates have oscillated about a semiarid mean. In the hyperarid cores of many desert regions, periods of increased humidity may have been of short duration, and represent excursions from a mean of aridity.

Knowledge of the record of Quaternary climatic changes in sand seas provides a means to understand the evolution of modern desert regions. It also provides information that can be used to improve interpretation of the record of ancient aeolian sandstones.

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