Regional Aeolian Dynamics in the Namib

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The Namib Sand Sea forms part of a regional-scale sand-transport system in which sand is transported inland from coastal source areas, fed ultimately by sand derived from the Orange River to the south, to accumulate in the large dunes of the central parts of the sand sea. Wind speeds and sand-transport rates decrease in the direction of the net sand transport, so the requirements of continuity dictate that sediment is deposited to form the sand sea. This model for the formation of the Namib Sand Sea can be applied to other sand seas.

INTRODUCTION

Sand seas are dynamic sedimentary bodies that form part of regional-scale sand-transport systems (Wilson, 1971; Fryberger and Ahlbrandt, 1979; Mainguet, 1984). The sand sea depositional system (Fig. 1) consists of sources and sinks for sediment, linked by a cascade of energy and materials that can be viewed in terms of sediment inputs and outputs, transfers and storages (Chorley and Kennedy, 1971). This paper considers the dynamics of the aeolian sediment transport system in the Namib in this framework, with an emphasis on the depositional system represented by the Namib Sand Sea.

THE SAND SEA DEPOSITIONAL SYSTEM

Inputs to the sand sea depositional system consist of energy and materials. The principal energy source is the kinetic energy of the wind, derived from regional and local scale atmospheric circulations driven by variations in the amount of solar energy received at the earth's surface. The accumulation of a desert sand sea requires an external source of sand-sized sediment that is actively renewed. The most important sources are fluvial and deltaic sediments (e.g., Capot-Rey, 1970; Glennie, 1970; Andrews, 1981; Wasson, 1983). Other sources include playas and sebkhas (e.g., McKee, 1966; Besler 1982; Wasson, 1983), and beaches (e.g., Inman, Ewing and Corliss, 1966; Lancaster, 1982). Some sand seas have internal sediment sources as a result of the deflation of interdunes and reactivation of older dunes (Wasson, 1983; Lancaster, 1988*a*). In the Sahara and Arabia, many sand seas receive inputs of sand from adjacent sand bodies (Fryberger and Ahlbrandt, 1979; Mainguet, 1984). Sediment is transferred, or transported, from source areas to sand seas by the wind. On satellite images, linear areas of high albedo, representing sand sheets and streaks, barchans, shadow dunes, and shrub coppice dunes often identify the position of such corridors for sand transport (Mainguet, 1984).

Two types of sediment storage take place in the sand sea system. The first is short-term storage along transport paths as sand drifts, shadows and streaks, as well as in small dunes. The second is as the dunes of the sand sea, which represent long-term sediment storage, similar to sediment storage in river flood-plains. Sand is transferred to storage, or deposited, by bedform climbing (migration of dunes or wind ripples in conditions of spatially decreasing sediment transport rates), and grainfall and grainflow deposition on avalanche faces (Hunter, 1977). Growth of large compound and complex dunes occurs by the merging or modification of smaller dunes (Mader and Yardley, 1985) and by vertical growth in opposed or complex wind regimes (Lancaster, 1983, 1988*b*). The sand sea as a whole accumulates by the migration of dunes in conditions of bedform climbing as a result of downwind decreases in sediment transport rates.

Although Wilson (1971), Mainguet and Chemin (1983) and Mainguet (1984) have shown that the same winds that transfer sand to the sand sea can also remove it, loss of sand from the downwind margins of many sand seas and dunefields is often minimal, especially if they are composed of migrating 'sand trapping' bedforms, such as crescentic dunes. Alternatively, the downwind margin of the sand sea may be determined by an increase in sand-transport rates as a result of regional climatic changes, such that sand removal exceeds the rate of replacement from upwind (Mainguet and Chemin, 1983). Loss of sand to fluvial or marine processes occurs in some sand seas (e.g., Glennie, 1970; Sarnthein and Diester-Haas, 1977; Andrews, 1981).

AEOLIAN DEPOSITIONAL SYSTEMS IN THE NAMIB

Sources of sand

Early investigators, mostly working in the southern parts of the Namib (e.g., Wilmer, 1893; Kaiser, 1926), concluded that the dunes to the north had developed from sands derived from the Namib between Lüderitz and the Orange River. Later workers (e.g., Gevers, 1936, and Logan, 1960) suggested that sediments derived ultimately from the Orange River provided the sand for the Namib Sand Sea. This model was developed by Rogers (1977), who showed the close similarities between the texture and mineralogy of shallow shelf, beach and dune sands in the southern Namib.

In contrast, Besler and Marker (1979) and Besler (1980) argued that the semi-consolidated red-brown sandstones of

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the Tsondab Sandstone Formation constituted the source of the dune sands. They argued that changes in dune sand colour, grain roundness and grain size from east to west reflected a pattern in which sands were transported from east to west by fluvial action and deposited in a series of alluvial fans that were later reworked by aeolian processes into the dominant S-N linear dunes.

Lancaster and Ollier (1983) considered possible sources of sand in fluvial and shallow marine sediments as well as the Tsondab Sandstone Formation and older bedrock. Most rivers draining from the escarpment to the east of the sand sea have small catchment areas and flow so infrequently that they do not constitute significant sources of sand-sized material for dune formation. The Kuiseb River sediments are distinctly different from the dune sands with the light fraction of the sands-sized material consisting of over 90 % quartz with the remainder being feldspar. The heavy mineral assemblage of Kuiseb River sediments is dominated by opaque minerals, biotite (20–40 %) and hornblende (< 20 %), derived from Kuiseb Formation schists. By contrast, biotite is rare or absent in the dune sands, which are dominated by quartz (90 %) with feldspar comprising 10 % or less of the total. The heavy mineral assemblage of the dune sands is dominated by clinopyroxene, garnet and opaque minerals (e.g., magnetite, ilmenite).

The mineralogy of the light fraction of the Tsondab Sandstone Formation is very similar to that of the dune sands, consisting mostly of quartz (90 %). The heavy minerals are dominated by opaques (> 80 %) with garnet, clinopyroxene, amphibole, epidote and rare zircon, tourmaline and rutile. Along the eastern margin of the sand sea, outcrops of the Tsondab Sandstone Formation may be an important local source for dune sands, but considerations of its mineralogy suggest that it is not a major source of sand for the sand sea.

Sands from the inner shelf between the Olifants and Orange Rivers contain pyroxene, amphiboles, magnetite, garnet and zircon, with rare rutile, epidote, tourmaline, ilmenite, kyanite and staurolite. Fine sands from north of the Orange River contain garnet, ilmenite, rutile, tourmaline, staurolite, pyroxene and amphibole (Rogers, 1977). Both these groups of samples have a composition very similar to the sands of the Namib Sand Sea, with dominant clinopyroxene, garnet and opaques (especially magnetite and ilmenite) and traces of other minerals (Lancaster and Ollier, 1983).

The sediments of the Orange River appear to be a major source of sand for the Namib Sand Sea (Rogers, 1977). The mean annual sediment discharge of the Orange River is 16,5 × 10^7 m^3 (Dingle and Hendey, 1984), equivalent to a sediment yield for the basin of 14,98 m^3 km^{-2} per annum. This rate is, however, inflated by recent soil erosion and is considerably in excess of the values predicted by the offshore sedimentary record, which indicate that sediment yields over the Neogene averaged 0,33 m^3 km^{-2} per annum (Dingle and Hendey, 1984). Some 7–15 m^3 of sand-sized sediment reach the sea via the Orange River each year (Rogers 1977). Vigorous longshore drift carries sand-sized material northwards for 200 km at a rate of 3025 m^3 per year 60 km north of Oranjemund (Rogers, 1977). The textural characteristics of nearshore shelf, beach and dune sands in this area are very similar (Rogers, 1977). Much of this material is deposited on the beaches of Prinzenbucht and Elizabeth Bay where it is deflated from the wide beaches and moved inland by strong and persistent southerly winds.

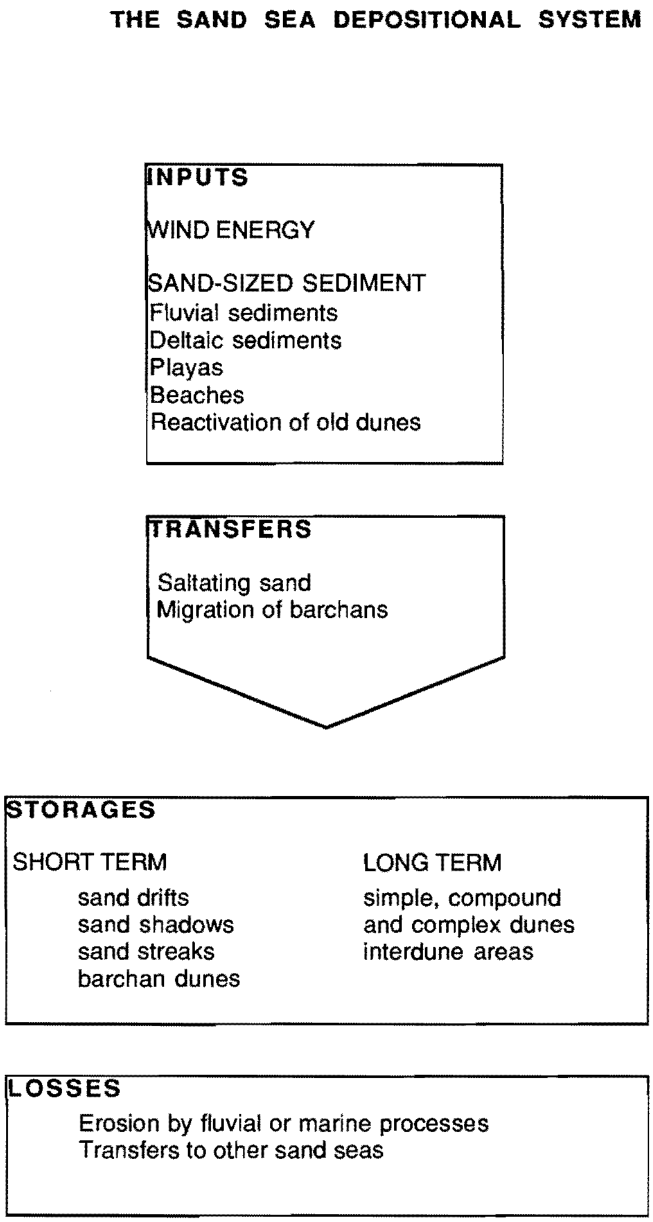

Fig. 1

Schematic illustration of the sand sea depositional system.

The pattern of sand movements in the sand sea

The regional pattern of potential sand-transport rates and directions, calculated from wind data using the formula of Bagnold (1953), reflects comparable patterns in the surface winds, with the effects of the stronger winds emphasized (Lancaster, 1985). Two major directional sectors of potential sand transport can be recognized: SSE-SW and E-NE; a third

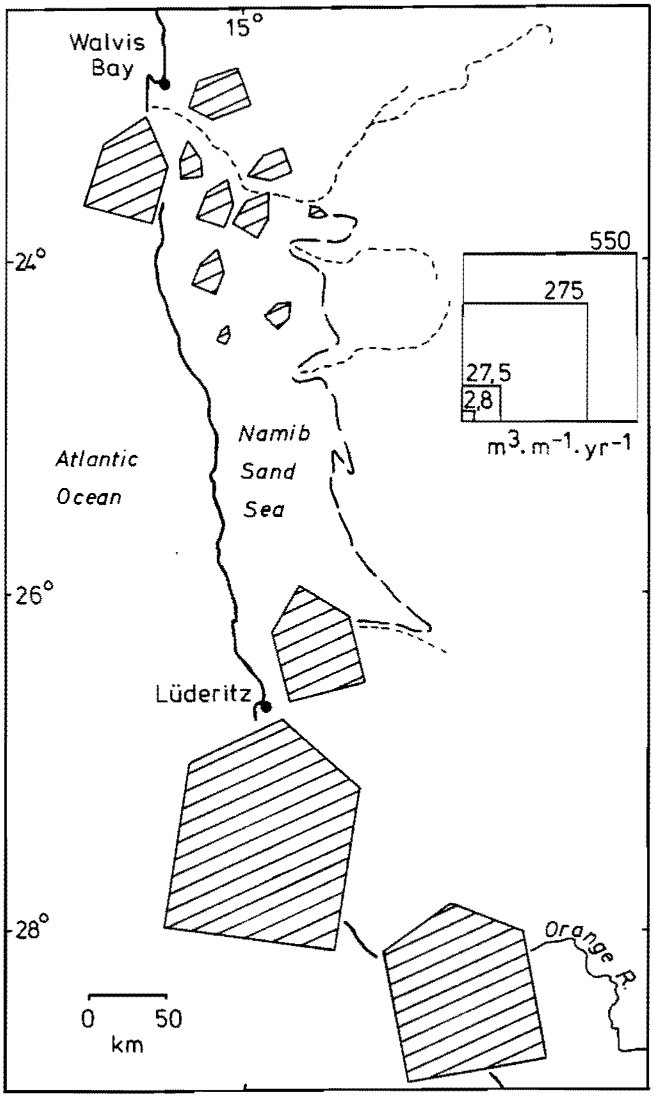

Fig. 2

Examples of wind regimes in different areas of the Namib Sand Sea. For location of stations see Fig. 7. Rose diagrams are for annual potential sand transport (calculated following Bagnold, 1953) from each wind direction. Arrow indicates direction to which annual resultant (vector sum) sand transport takes place. **A**: wind regimes in areas of crescentic dunes; **B**: linear dunes; **C**: star dunes.

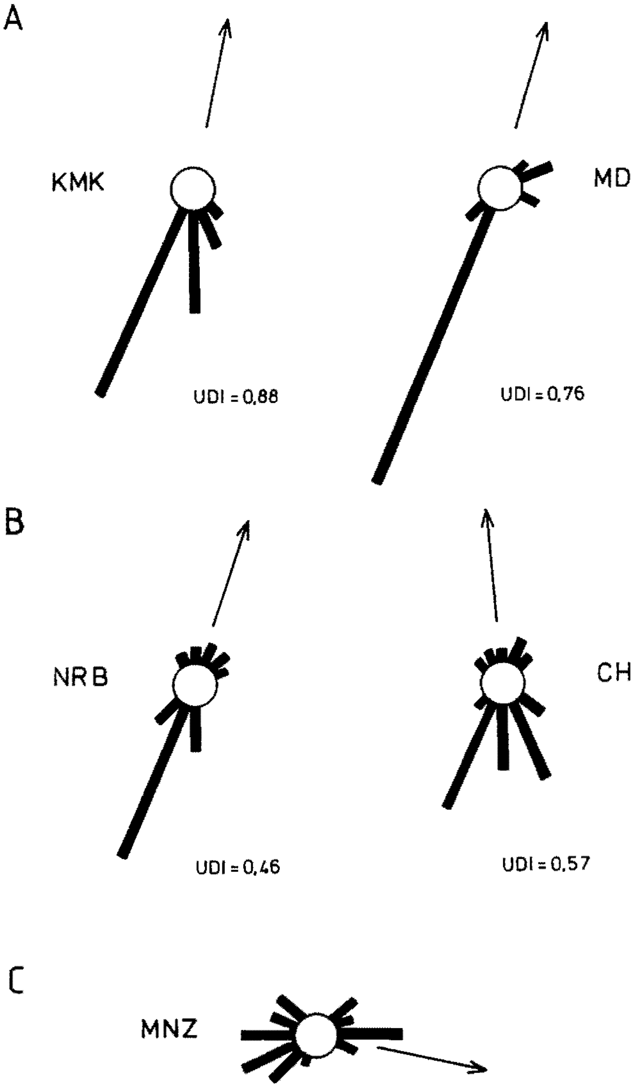

Fig. 3

Regional pattern of the magnitude and direction of resultant (vector sum) potential sand transport.

sector, N-NNW, is locally important. Figure 2 illustrates typical annual sand-transport patterns in different parts of the sand sea.

The SSE-SW sector is the most important throughout the sand sea. It is the dominant sand-transport sector all the year near the coast where it accounts for 80–90 % of sand transport. The proportion of sand transport from this sector decreases to 55–65 % in central areas and 35–40 % along the eastern margin of the sand sea. The E-NE sector is of minor importance at coastal stations (< 10 % of annual sand transport), but comprises 10–20 % of annual sand transport in central parts of the sand sea and 30–55 % on its eastern margins. On the northern edge of the sand sea this sector is dominant, and accounts for 60–65 % of annual sand transport. In these areas, sand transport from N-NNW directions also occurs (6–10 % of the annual total).

The importance of the directional sectors varies seasonally in response to changes in the strength and persistence of different components of the regional wind regime. The degree of seasonal change is least on the coast, although even here sand transport from easterly directions can account for 30–40 % of sand transport in July and August. Inland, the seasonal variability is much greater. Sand transport from S-SW directions dominates in the period September–April (> 90 % of sand transport in the period December–January). As the amount of sand transport from the S-SW sector decreases in winter (to

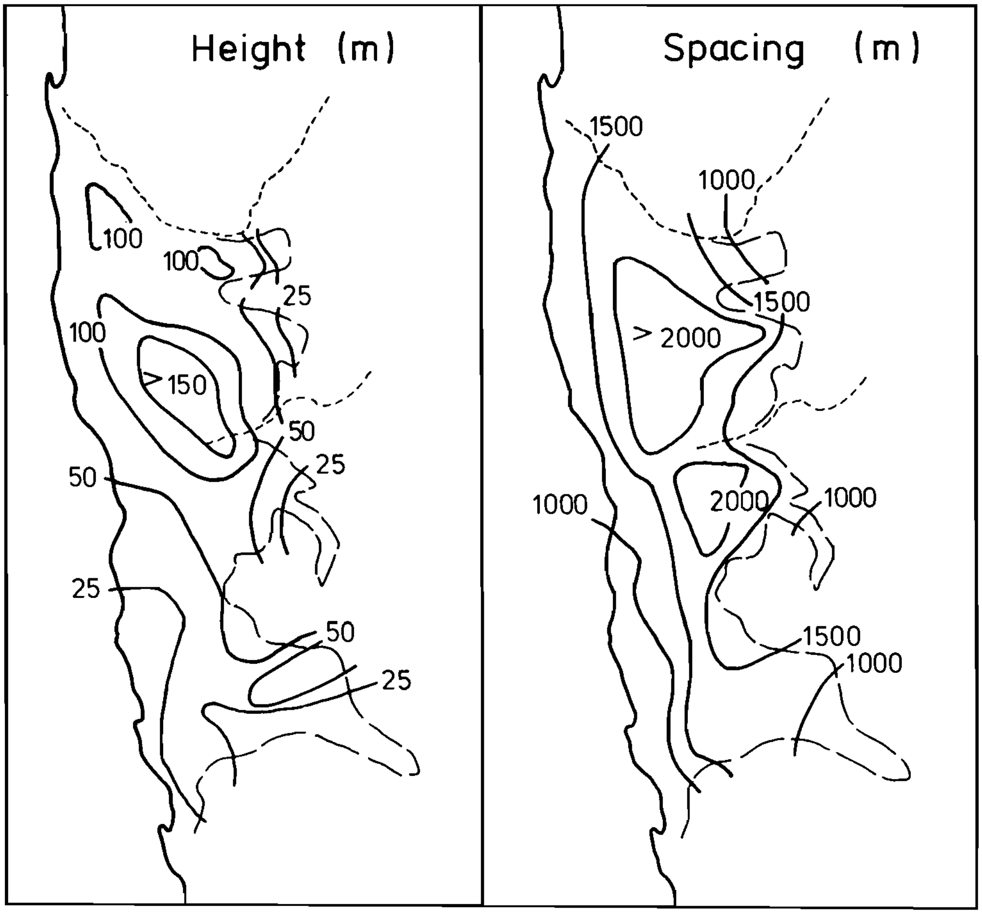

Fig. 4

Spatial variation in dune height and spacing in the Namib Sand Sea. Data on dune height from field survey, extrapolated to other areas from regressions of dune height and spacing. Data on dune spacing from aerial photographs.

10 % of the total), so the amount from directions between E and NE increases, reaching a maximum of 30–50 % in June or July.

The magnitude of potential sand-transport rates varies considerably over the region, in response to variations in the strength and persistence of sand-moving winds. Total annual potential sand-transport rates are at a maximum in the southern Namib, (> 330 $m^3.m^{-1}.yr^{-1}$), reflecting the high energy of the wind regime in this part of the desert. They decrease inland and to the north. In the northern parts of the sand sea, annual potential sand-transport rates are generally much lower, but still exhibit a sharp decrease inland from 120 $m^3.m^{-1}.yr^{-1}$ at the coast, through a wide zone where they are 14–28 $m^3.m^{-1}.yr.^{-1}$, to 5,5–8,25 $m^3.m^{-1}.yr^{-1}$ in the eastern parts of the sand sea. The magnitude of potential sand-transport rates also varies seasonally. They are at a maximum at coastal stations in November to February and at a minimum in winter. Inland, maximum potential sand transport occurs in the period December to January or locally September, with a subsidiary peak in July.

The annual resultant (vector sum) direction of sand transport (Fig. 3) is almost everywhere towards the NE or NNW, reflecting the dominance of sand transport from the southerly sector. The magnitude of the annual resultant sand transport is greatest for the high energy, unimodal wind regimes of southern and coastal areas and least for the complex wind regimes of the eastern and northern margins of the sand sea. The direction of resultant sand transport also changes seasonally. In the summer months, sand transport at all stations is towards the N to NE. The magnitude of both total and resultant sand-transport rates are also at a peak at this time of year. During the winter months, the resultant sand transport at most stations is low and directed towards the SW or W. However, at stations on the northern boundary of the sand sea maximum resultant sand transport occurs in June or July.

The ratio between resultant and total potential sand-transport rates (the RDP/DP ratio of Fryberger (1979) or the unidirectional index (UDI) of Wilson (1971)) is an index of the effectiveness of sand transport for a station. A UDI of 1,0 indicates that all sand transport takes place in the resultant direction; a UDI of 0,25 means that 75 % of sand-transporting winds cancel each other out. In the Namib Sand Sea, sand-transport regimes can be divided into those with high total and net sand transport (high UDI) and those with low total and net

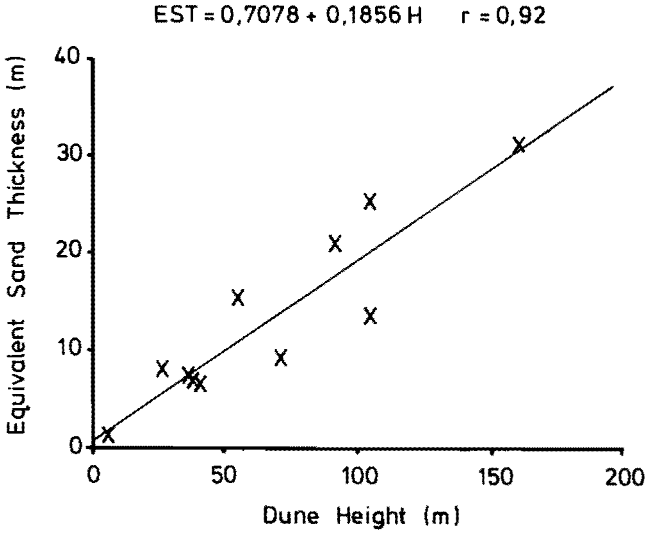

Fig. 5

Relation between dune height and equivalent sand thickness (EST) from surveyed cross-sections of dunes.

sand transport (low UDI). Those in the coastal areas of the Namib are high energy, narrow unimodal with an annual UDI > 0,70 (Fig. 2a). In the central parts of the sand sea (Fig. 2b), they are bimodal high to moderate energy (annual UDI 0,40–0,60), and complex (Fig. 2c) in the eastern and central parts of the sand sea (annual UDI 0,20–0,30).

The pattern of deposition in the sand sea

Dune height and spacing vary together in a systematic way in the Namib Sand Sea (Fig. 4). Dunes are highest and most widely spaced in the central and some northern parts of the sand sea, with progressively lower and more closely spaced dunes towards the margins. In the southern parts of the sand sea, most dunes are less than 50 m high, except for the groups of star dunes along the eastern margins. Dune height increases to a maximum of 180–200 m in the area between Sossus Vlei and the Tsondab valley. A smaller area of large linear and star dunes occurs between Tsondab Vlei and the Kuiseb River. Dune height and spacing decrease towards the eastern margins of the sand sea where, except for areas of star dunes, most dunes are less than 25 m high.

Data from surveyed cross-sections of dunes in the Namib indicate that their cross-sectional area increases exponentially with dune height. The amount of sand contained in the dunes of an area is represented by the equivalent (or spread out) sand thickness (EST) obtained by dividing cross-sectional area by dune spacing. There is a good correlation between dune height and EST (Fig. 5). Thus, large dunes, even though they are widely spaced, represent a greater accumulation of sand than do smaller, more closely spaced examples. The relation between dune height and equivalent sand thickness can be used to estimate equivalent sand thickness for the sand sea as a whole (Fig. 6). This is a minimum figure for many areas, as it does not take into account sand that has accumulated below the dunes and in interdune areas. The accumulated thickness of sand over most of the central parts of the sand sea exceeds 20 m and is more than 30 m north and northwest of Sossus Vlei. Apart from small areas of star dunes, equivalent sand thickness in the southern parts of the sand sea is less than 10 m. The total amount of sand in the Namib Sand Sea is in the order of 600–700 km^3.

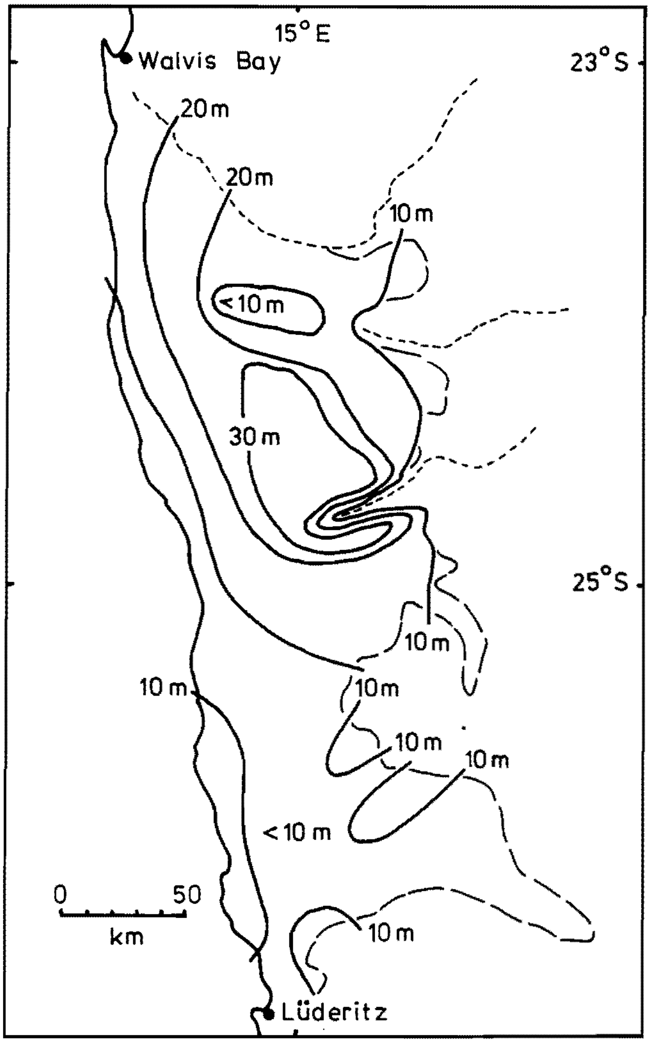

Fig. 6

Spatial variation in equivalent sand thickness for the Namib Sand Sea, representing amount of sand in dunes. Map compiled from data in Fig. 4 and relationship in Fig. 5.

Losses of sand from the sand sea

Loss of sand to fluvial or marine processes occurs in some parts of the Namib Sand Sea. Barchans and transverse dunes prograde onto sebkhas and salt marshes on the northern margins of the Namib Sand Sea (McKee, 1982) and dunes are being actively eroded by wave action on its western margin between Sylvia Hill and Sandwich Harbour (Rogers, 1977). Fluvial erosion of the tips of linear dunes occurs along the Kuiseb River in periods of flow in the river (Ward and Von Brunn, 1985).

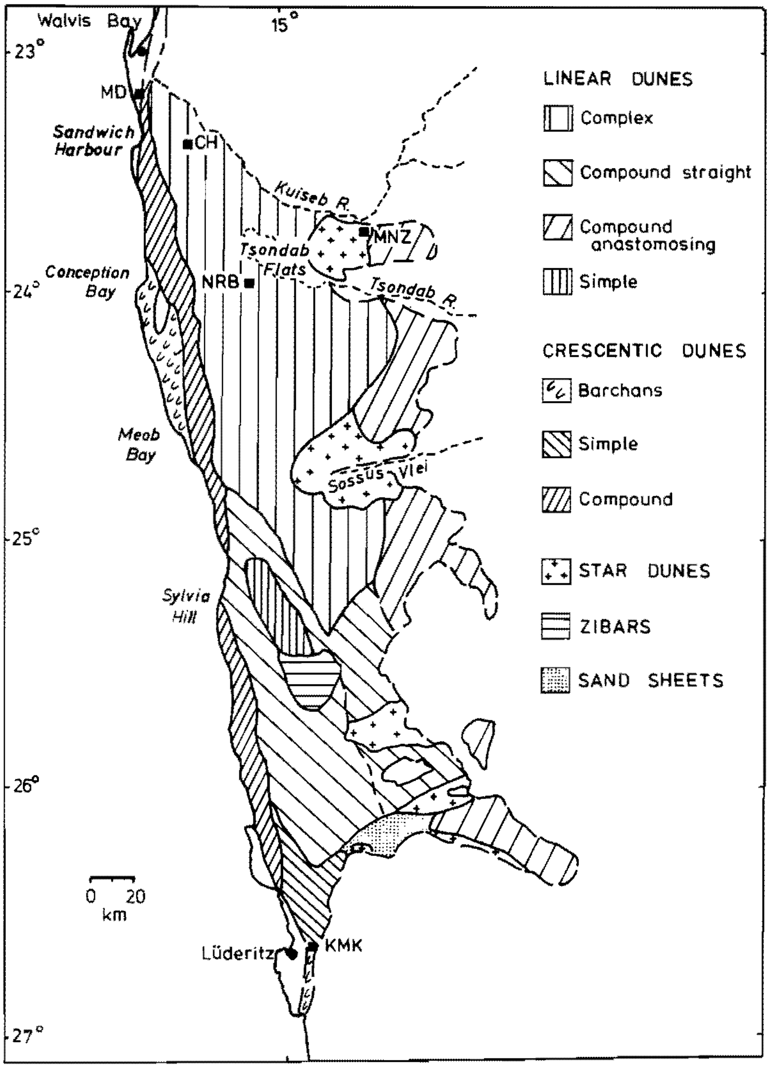

Fig. 7

Spatial variation in dune types in the Namib Sand Sea (after Lancaster, 1983). Location of stations used for Fig. 2 shown.

DISCUSSION

Data on the regional patterns of sand transport and deposition can be used to interpret patterns of dune morphology and morphometry. In turn, this information can be combined to produce a model for the accumulation of the sand sea.

Controls on dune morphology

The pattern of dunes of different types and the spatial variation in their size, spacing and alignment in a sand sea are the surface expression of the factors that control its dynamics and accumulation (Lancaster, 1989). Studies of the occurrence of each major dune type (crescentic, linear or star) in a variety of sand seas show that dune type is largely controlled by the directional variability of the wind regime, expressed as the ratio between resultant and total potential sand transport (UDI), with grain size, sand supply and vegetation cover playing a subordinate role (Fryberger, 1979; Lancaster, 1983; Wasson and Hyde, 1983).

Three major dune types, classified according to the scheme of McKee (1979), occur in the Namib Sand Sea: crescentic, linear and star, in simple, compound and complex varieties (Fig. 7). There are also small areas of zibars, sand sheets and shrub coppice dunes (Lancaster, 1983). Crescentic dunes of simple and compound form cover 13 % of the area of the sand sea, in a strip up to 20 km wide along the coast and also further inland where dune patterns are disturbed by river valleys (e.g., on the Tsondab Flats). Linear dunes on S-N to SE-NW alignments are the dominant dune form in the Namib Sand Sea and cover 74 % of its area. Compound linear dunes cover 35 % of the sand sea in its southern and eastern sectors. Large complex linear dunes, with stellate peaks at intervals and crescentic dunes on their eastern flanks dominate in central and northern parts of the sand sea and are found over 37 % of its area. Star dunes are found in groups along the eastern margins of the sand sea, and cover some 9 % of the sand sea.

Comparison of the pattern of dune types (Fig. 7) and the directional variability of the wind regime (Fig. 2) shows that barchans and crescentic dunes occur in unidirectional wind regimes near the coast; linear dunes dominate over much of the sand sea, where bi-directional winds occur; and star dunes are associated with multi-directional wind regimes along the eastern margin of the sand sea (Fig. 8). These comparisons are most easily demonstrated for the northern parts of the sand sea (Lancaster, 1983), and appear to apply in the southern areas of the sand sea, although wind data for these areas are sparse.

The relations between mean dune height and annual total and resultant potential sand transport for the Namib Sand Sea show that large dunes are found in areas where annual potential sand-transport rates are low and small dunes occur in areas of high sand-transport rates. Similarly, equivalent sand thickness (EST) varies inversely with total potential sand-transport rates. In the Namib Sand Sea, there is a progressive reduction in potential sand-transport rates from south to north and west to east such that central areas of the sand sea, with their large dunes, are areas of low total and net potential sand transport (Lancaster 1983, 1988*b*). Areas of low dunes in the southern part of the sand sea are also areas of high annual total and net potential sand-transport rates. These are zones through which sand is passing on its way to the depositional centre of the sand sea in its northern and central sector. The distribution of large dunes in the sand sea therefore reflects the spatial pattern of deposition. Their size is a result of long-continued growth in conditions of abundant

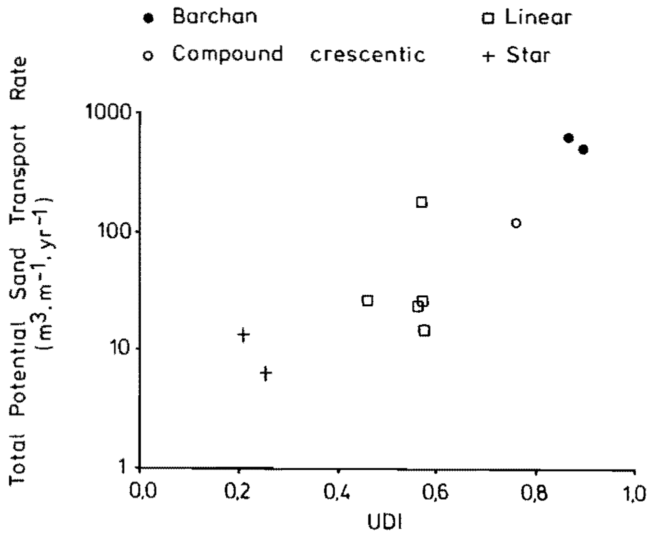

Fig. 8

Relations between dune type, unidirectional index (UDI) and total annual potential sand transport. Based on wind data in Lancaster (1985).

sand supply and a wind regime that promotes deposition on the dune. Growth of the large linear dunes appears to occur as a result of deposition by the migration of superimposed crescentic dunes on the east flank of complex linear dunes from areas of high to low sand-transport rates (Lancaster, 1988*b*).

CONCLUSIONS

In the Namib Sand Sea, data from studies of winds and sand-transport rates can be combined with information on dune morphology and sediments to develop a model of sand sea formation in which sand is moved inland from source areas, fed ultimately by the Orange River, to accumulate in large complex linear and star dunes in the centre of the sand sea.

Throughout most of the sand sea, the annual resultant direction of sand transport is towards the north and northeast. The rate of sand transport decreases in the region of the Namib Sand Sea from south to north and from the coast inland. In addition, there is a parallel increase in the directional variability of winds and sand-transport rates. Sand is therefore transported from southern and western coastal areas towards central, northern and eastern parts of the sand sea. As sand-transport rates decrease in the mean transport direction, the requirements of the conservation of sediment dictate that deposition occurs. Sand is also being transported into areas where winds are opposed in direction. Consequently, once sand reaches such areas, it will tend to remain there and add to the dunes. These are the areas of large dunes and thick sand cover.

This model has more than a local significance. It is supported by studies of the rock record (e.g., Porter, 1986) and of sand seas and dunefields in North America (e.g., Lancaster, Greeley and Christensen, 1987). The depositional centres of sand seas are areas of low total and net sand-transport rates, and are characterized by large dunes that are the result of long-continued accumulation of sand.

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REFERENCES

ANDREWS, S., 1981. Sedimentology of the Great Sand Dunes, Colorado. *S.E.P.M. Special Publication* 31: 279–291.

BAGNOLD, R. A., 1953. Forme des dunes de sable et régime des vents. *Actions Eoliennes, Centre National de Recherches Scientifiques, Colloques Internationaux* 35: 23–32.

BESLER, H., 1980. Die Dünen–Namib: Entstehung und Dynamik eines Ergs. *Stuttgarter Geographische Studien*, 96.

BESLER, H., 1982. The north-eastern Rub' al Khali within the borders of the United Arab Emirates. *Zeitschrift für Geomorphologie* 26: 495–504.

BESLER, H. and MARKER, M. E., 1979. Namib sandstone: a distinct lithological unit. *Transactions of the Geological Society of South Africa* 82: 155–160.

CAPOT-REY, R., 1970. Remarques sur les ergs du Sahara. *Annales de Géographie* 79: 2–19.

CHORLEY, R. J. and KENNEDY, B. A., 1971. *Physical geography: a systems approach.* Prentice Hall, London.

DINGLE, R. V. and HENDEY, Q. B., 1984. Late Mesozoic and Tertiary sediment supply to the eastern Cape basin (SE Atlantic) and palaeo-drainage systems in southwestern Africa. *Marine Geology* 56: 13–26.

FRYBERGER, S. G., 1979. Dune forms and wind regime. *In:* McKEE, E. D., ed., A study of global sand seas. *US Geological Survey Professional Paper* 1052: 137–140.

FRYBERGER, S. G. and AHLBRANDT, T. S., 1979. Mechanisms for the formation of eolian sand seas. *Zeitschrift für Geomorphologie* 23: 440–460.

GEVERS, T. W., 1936. The morphology of western Damaraland and the adjoining Namib Desert. *South African Geographical Journal* 19: 61–79.

GLENNIE, K. W., 1970. *Desert sedimentary environments.* Developments in Sedimentology 14. Elsevier, Amsterdam.

HUNTER, R. E., 1977. Basic types of stratification in small eolian dunes. *Sedimentology* 24: 361–388.

INMAN, P. L., EWING, G. C. and CORLISS, J. B., 1966. Coastal sand dunes of Guerrero Negro, Baja California, Mexico. *Geological Society of America, Bulletin* 77: 787–802.

KAISER, E., 1926. *Die Diamantenwüste Südwest-Afrikas.* Reimer, Berlin.

LANCASTER, N., 1982. Dunes on the Skeleton Coast, Namibia (South West Africa): geomorphology and grain size relationships. *Earth Surface Processes and Landforms* 7: 575–587.

LANCASTER, N., 1983. Controls of dune morphology in the Namib sand sea. *In:* BROOKFIELD, M. E. and AHLBRANDT, T. S., eds, *Eolian sediments and processes.* Developments in Sedimentology 38. Elsevier, Amsterdam.

LANCASTER, N., 1985. Winds and sand movements in the Namib sand sea. *Earth Surface Processes and Landforms* 10: 607–619.

LANCASTER, N., 1988*a*. Development of linear dunes in the southwestern Kalahari, southern Africa. *Journal of Arid Environments* 14: 233–244.

LANCASTER, N., 1988*b*. The development of large aeolian bedforms. *Sedimentary Geology* 55: 69–90.

LANCASTER, N., 1989. *The Namib sand sea: dune forms, processes and sediments.* A. A. Balkema, Rotterdam.

LANCASTER N. and OLLIER, C. D., 1983. Sources of sand for the Namib sand sea. *Zeitschrift für Geomorphologie* Supplement 45: 71–83.

LANCASTER, N., GREELEY, R. and CHRISTENSEN, P. R., 1987. Dunes of the Gran Desierto sand sea, Sonora, Mexico. *Earth Surface Processes and Landforms* 12: 277–288.

LOGAN, R. F., 1960. *The central Namib Desert, South West Africa.* National Academy of Sciences, Washington D.C.

McKEE, E. D., 1966. Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas). *Sedimentology* 1: 1–69.

McKEE, E. D., 1982. Sedimentary structures in dunes of the Namib Desert, South West Africa. *Geological Society of America, Special Paper* 186.

McKEE, E. D., 1979. Introduction to a study of global sand seas. *In:* McKEE, E. D., ed., A study of global sand seas. *US Geological Survey Professional Paper* 1052: 3–19.

MADER, D. and YARDLEY, M. J., 1985. Migration, modification and merging in aeolian systems and the significance of the depositional mechanisms in Permian and Triassic dune sands of Europe and North America. *Sedimentary Geology* 43: 85–218.

MAINGUET, M., 1984. Space observations of Saharan aeolian dynamics. *In:* EL BAZ, F., ed., *Deserts and arid lands.* Nyhoff, The Hague.

MAINGUET, M. and CHEMIN, H. C., 1983. Sand seas of the Sahara and Sahel: an explanation of their thickness and sand dune type by the sand budget principle. *In:* BROOKFIELD, M. E. and AHLBRANDT, T. S., eds, *Eolian sediments and processes.* Developments in Sedimentology 38. Elsevier, Amsterdam.

PORTER, M. L., 1986. Sedimentary record of erg migration. *Geology* 14: 497–500.

ROGERS, J., 1977. Sedimentation on the continental margins off the Orange River and the Namib Desert. *Joint Geological Survey/University of Cape Town Marine Geoscience Group Bulletin* 7.

SARNTHEIN, M. and DIESTER HAAS, L., 1977. Eolian sand turbidities. *Journal of Sedimentary Petrology* 47: 868–896.

WARD, J. D. and VON BRUNN, V., 1985. Sand dynamics along the Kuiseb River. *In:* HUNTLEY, B. J., ed., *The Kuiseb environment: the development of a monitoring baseline.* South African National Scientific Programmes Report No. 106, Pretoria.

WASSON, R. J., 1983. Dune sediment type, sand colour, sediment provenance and hydrology in the Strzelecki-Simpson dunefield, Australia. *In:* BROOKFIELD, M. E. and AHLBRANDT, T. S., eds, *Eolian sediments and processes.* Developments in Sedimentology, 38. Elsevier, Amsterdam.

WASSON, R. J. and HYDE, R., 1983. Factors determining dune types. *Nature* 304: 337–339.

WILMER, H. C., 1893. The relationship of the sand dune formation on the south west coast of Africa to local wind currents. *Transactions of the South African Philosophical Society* 5: 326–329.

WILSON, I. G., 1971. Desert sandflow basins and a model for the development of ergs. *Geographical Journal* 137: 180–197.