Adhesion-ripple and barchan-dune sands of the Recent Namib (SW Africa) and Permian Rotliegend (NW Europe) Deserts

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CONTENTS

SUMMARY

Sequences of interbedded adhesion-ripple sands and barchan-dune sands, now forming in the coastal Namib Desert just south of Walvis Bay, also occur in a wide belt of Permian Rotliegend desert deposits in the south-central part of the North Sea Basin of NW Europe.

In the Namib Desert, the adhesion-ripple sands accumulate on a wide supratidal flat, laterally transitional to a barchan-dune field. A concentrated sea-water-derived brine (4,7 to 5,2 times denser than sea-water) occurs 30 to 50 cm below the surface. In the vadose zone, precipitation of aragonite, high-magnesian calcite, gypsum and bassanite and dolomitisation occurs; mainly halite crystallises at the surface. The surface cementation with halite plays an important role in the formation of the adhesion-ripple sands and in the preservation of foresetted beds of sand originally deposited as the basal parts of barchan dunes.

On the basis of a close similarity in sedimentary structure and the type of early diagenesis, it is concluded that the dominating environmental factors of the investigated Namib and Rotliegend deposits (wide, low-lying plains having near-surface groundwater tables, and a desert climate) are the same.

1. INTRODUCTION

One of the characteristic facies of the Permian Rotliegend desert deposits in NW Europe consists of interbedded adhesion-ripple and dune sands. This facies, present in an east-west oriented, wide belt in the south-central part of the North Sea, has been interpreted as coastal, in the sense of being adjacent to a large, saline, inland body of water (Glennie, 1972).

Adhesion-ripple sand deposits are presently forming in close association with barchan dunes in the coastal area of the Namib Desert, just south of Walvis Bay, SW Africa (Fig. 1). The main object of this paper is to show that if these recent desert-sand deposits were accumulating in a subsiding area, eolian sequences similar to those of the Rotliegend would form; this applies both to the sedimentary structures and to the early cementation of the sands with evaporite minerals.

In the Walvis Bay area, the formation of foresetted dune-sand beds from the basal parts of barchan dunes, a process not yet described from recent deposits, takes place. Dune-base cementation, partly with gypsum and bassanite, but mainly with halite, appears to play an important part in this process. A high moisture content in the basal parts of dunes has been suggested as a cause for the formation of foresetted dune-sand beds, by Peirce (1964) and Stokes (1968). Mention of dune-base cementation similar to that found at Walvis Bay (gypsum and rock salt, barchan dunes in the

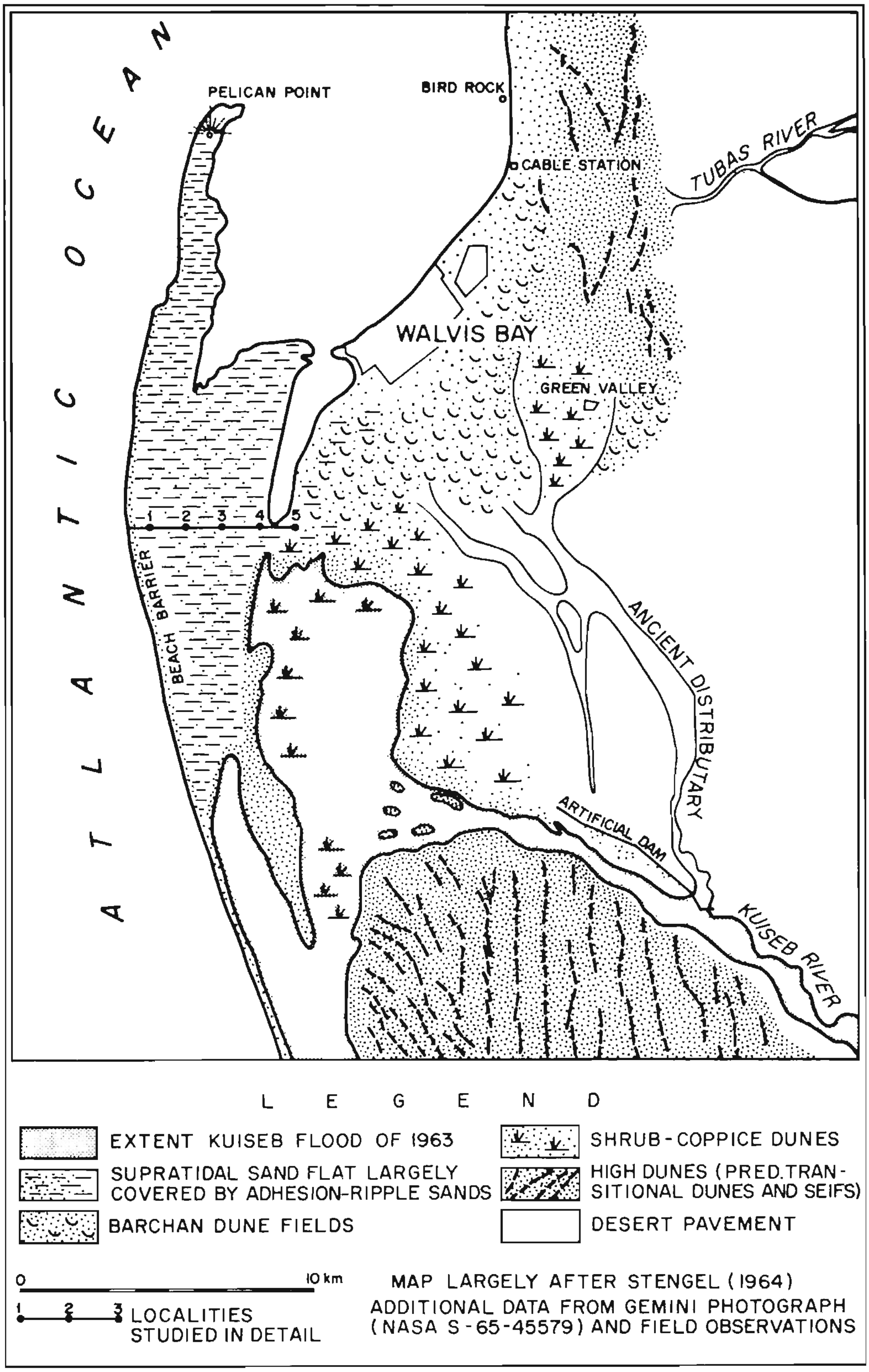

Figure 1. Depositional environments, coastal Namib Desert, Walvis Bay area.

Rub'al Khali, Saudi Arabia) is made in the comprehensive study of eolian sand control by Kerr and Nigra (1952).

The term 'adhesion ripples' is applied to the sedimentary structure formed when wind-blown sand adheres to either continuously or temporarily moist, planar surfaces. Accumulation of sand in this way is common in low-lying coastal and inland areas of deserts (coastal and inland sabkhas; Glennie, 1970). Although the term adhesion ripples is a literal translation of the German 'Haftripplen' (Reineck, 1955), the morphology of our present examples is closer to that of Reineck's 'Haftwarzen'.

A detailed discussion of the morphology and climate of the central part of the Namib Desert has been presented by Logan (1960); climatologic data are also given by Stengel (1964) and Schulze (1969).

2. THE NAMIB DESERT COASTAL DEPOSITS, SW AFRICA

A great variety of desert depositional environments is found in the immediate vicinity of Walvis Bay. North of the town, there is a dune field 20 km long and about 5 km wide. It is composed mostly of high, irregularly-shaped dunes and some seif dunes (Fig. 1). The area depicted in Figure 1 includes the northernmost tip of the main Namib Desert dune field, which stretches southwards for 400 km, and is between 45 and 130 km wide. Except for a belt along the coast where northwest-southeast-striking transverse dunes are found, this field consists largely of high, approximately north-south trending seif dunes.

A complex depositional pattern occurs between the two dune fields, south of Walvis Bay (Fig. 1). Large parts of this area are inundated when the Kuiseb River is in full flood, which happens on average, since 1837, once in 9 years (after data of Stengel, 1964). During full flood, considerable quantities of biotite-rich sand, silt, and clay are deposited. When the area has dried up, wind action takes over, reactivating the small shrub-coppice dunes which abound here, and supplying sand to the barchan dune field. North of the shrub-coppice dune field, a belt of well-developed barchan dunes surrounds Walvis Bay on the landward side. The barchan dunes, as well as the transverse dunes of the coastal belt further south, show avalanche slopes dipping predominantly to the north-northeast (dunes migrating in this direction), in response to the 5-50 km/hr southwesterly winds which are common in the afternoon, both in winter and summer (Logan, 1960). The barchan dune field grades into the dune field north of Walvis Bay, the barchans gradually losing their characteristic geometrical forms and developing, via transverse, into high, irregularly-shaped dunes.

At the southwestern end of the barchan dune field, dunes can be seen forming on the extreme eastern part of the supratidal sand flat. The supratidal-sand-flat deposits, consisting largely of adhesion-ripple sands, extend beyond their present boundary with the barchan dune field, the dune field having been built out partly across them. In this area, and on the sand flat, more detailed observations have been carried out along the section shown in Figure 1 (localities 1-5).

2.1. Supratidal sand flat; adhesion-ripple sands

The supratidal sand flat is an extensive, almost featureless plain composed of sand. The surface is estimated to be between 1 and 2 m above mean high tide. Normal spring tides cover restricted parts of the sand flat, especially in the north. It is not known how far spring tides and storm spring tides would extend. However, thin continuous sand beds intercalated between adhesion-ripple sands are thought to be due to reworking by such tides, and extend up to locality 4 (Fig. 2A). A concentrated brine occurs everywhere at shallow depths, with the water table usually occurring between 30 and 50 cm below the surface (p. 10).

Pits dug into the sands of the flat have shown that horizontally-laminated beach sands are found from the surface to a depth of at least 1 m, up to 2,5 km from the coast. Further inland, adhesion-ripple sands appear at the surface, regularly increasing in thickness from a few centimetres to more than 1 m at locality 4. At some localities, wind-deposited, elongate sand lenses up to 50 cm high occur, both on beach sands and adhesion-ripple sands. They are horizontally laminated. The presence of beach sands below the adhesion-ripple sands could still be demonstrated between localities 3 and 4. Since the beach sands were deposited between low and high tides, and the adhesion-ripple sands are wind-transported sediment, it follows that the mutual relationship just described indicates an outbuilding of the coast, and consequently an overall regressive development.

The size and surface morphology of the adhesion ripples vary considerably (Figs. 2A and B). Locally the ripples are as small as 0,5 cm, but they can be up to 12 cm in cross-section and 6 cm high. Most ripples are between 2 and 6 cm in cross-section, and between 1 and 3 cm high. The majority of the ripples occur in the form of round or oval humps, in patterns of varying density. In cross-section, the adhesion-ripple sands show a distinctive, irregular, lenticular bedding (Fig. 2A). Differences in size and shape of the lenticles correspond to the differences in size and shape of the original adhesion ripples.

When the air is dry, which is mainly in the afternoon, the surface of the adhesion ripples is friable to hard. They are cemented mainly with halite, drawn to the surface by capillary action from the brine which occurs at shallow depths. The afternoon is also the time when sand transport takes place, under the influence of the southwesterly breeze. Wind action spreads loose sand evenly over wide areas of the sand flats, locally eroding existing adhesion ripples into elongate shapes (Fig. 2A, inset). When the relative humidity of the air increases to more than approximately 75%, which is common at night and during the mornings (Logan, 1960), the ripples become moist and soft due to the hygroscopic action of the halite cement*.

Following wetting of the sands, part of the newly-deposited loose sand overlying the adhesion ripples is cemented in place by the recrystallisation of the halite during the succeeding dry afternoon. The still loose, non-cemented sand can be moved on, some of it ultimately accumulating in the form of barchan dunes.

2.2. Barchan dunes

The barchan dunes in the vicinity of locality 5 are of the order of several hundreds of metres apart; north of locality 5, the dune pattern becomes denser, many dunes interfering laterally or even overriding each other. Most dunes are between 10 and 30 m high. The interdune areas are planar and usually almost free from loose, blown sand.

The interdune areas at locality 5 have two types of surface: (a) adhesion ripples, with major parts of the ripple fields non-active, and (b) wide areas of curved, but parallel, low (1-3 cm) asymmetrical ridges with a radius of curvature of 100 to 300 m. The ridges are 1 to 10 cm apart, their concave sides oriented to the north to northeast. The ridges closely resemble the 'tracks' described and illustrated by Kerr and Nigra (1952) from the Rub'al Khali, Saudi Arabia, but are much smaller.

Digging in the sands that have the surface expression of curved ridges invariably shows them to have foresetting at 30-34°, all dips occurring in the direction of the concave side of the curve; the sands vary in thickness between 10 and 100 cm. On the basis of their geometry, these sand beds are regarded as the basal parts of barchan dunes that were preserved here when the larger upper parts of the dunes moved on. After exposure of the upper surfaces of the basal parts of the dunes, adhesion ripples could develop on them. Over wide areas adhesion ripples are absent, in others they are extremely thin and have a patchy distribution, while in yet other parts they reach thicknesses of up to 100 cm on top of the truncated barchan-dune sands.

Figure 2B shows a section in a pit dug at the base of the avalanche slope to the north side of a dune that we studied in detail**.

At the bottom of the pit there is a biotite-rich silty clay (black), no doubt a deposit from one of the Kuiseb floods (Fig. 1). Directly above it lies foresetted dune sand, which is overlain by a thin horizon of adhesion ripples. This sequence will soon be covered by the barchan dune, which is advancing from the right.

In the upper part of the truncated, foresetted dune sand, a light-coloured crust can be seen, which on examination appears to consist of dune sand cemented with halite and traces of gypsum and bassanite. A similar, but very much thinner, crust occurs in the surface of the adhesion-ripple sand (Fig. 2B). This thin upper crust probably grows at the expense of the thicker crust below, deriving the salt by means of a capillary brine. Such halite crusts characterise the entire surface of the interdune areas. Their role in the formation of adhesion ripples has already been discussed (p. 7). Where the crust is associated with areas consisting of small, curved sand ridges, ot is clear that it protects these beds of former basal dune sands from further deflation, and thus renders them potentially preservable for the geological record.

In addition, cementation mainly with halite probably plays an important part in the actual formation of the dune-base sand beds from the barchan dunes. On the low-angle (8-12°), upwind slopes of many barchan dunes in the area, thin, halite-cemented laminae (internal foreset laminae) protrude above the dune surface. Some metres above the true base, these cemented laminae are quite fragile and fall apart easily when touched. Nearer the base of the dunes, however, the laminae are stronger. It is thought that this preferential cementation of certain laminae is due to the near-surface crystallisation of halite from capillary brines, drawn up from below. It can be argued that the downward-increasing cementation in the lower parts of the windward slopes of the barchan dunes will set a limit to the depth of deflation, thus increasing the possibility of preservation of the basal part of the dunes. In this way a deflation surface with curved sand ridges (the ridges being an expression of the best-cemented laminae) could be formed. However, no real proof of this process, in the form of upwind barchan-dune slopes showing a 'knick' between a cemented basal part and a still-active dune sand higher up, has been observed in the present dune field. It may well be that the larger amount of cementation occurs only after periodically higher water tables (Kerr and Nigra, 1952).

The relationships between the dune sands and adhesion-ripple sands just described are significant in that they are thought to illustrate the principle by which parallel-bedded sequences composed of these sands may form.

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* At 30°C, the vapour pressure of a saturated NaCl solution (23,9 mm Hg) is three quarters of that of pure water at the same temperature (31,83 mm Hg) (Washburn, 1928, pp. 369-370). It follows that, below a relative humidity of 75%, halite will be dry, while above this value it will be moist or wet (going into solution). At other temperatures, in the 0-100°C range, only slightly different values of humidity are obtained. When, due to insolation, the salt is warmer than the overlying air, it will tend to be dry at somewhat higher humidities (R. B. de Boer, pers. comm.).

**This dune was: 220 m long, 190 m wide and 20 m high; the avalanche slope was 14 m long.

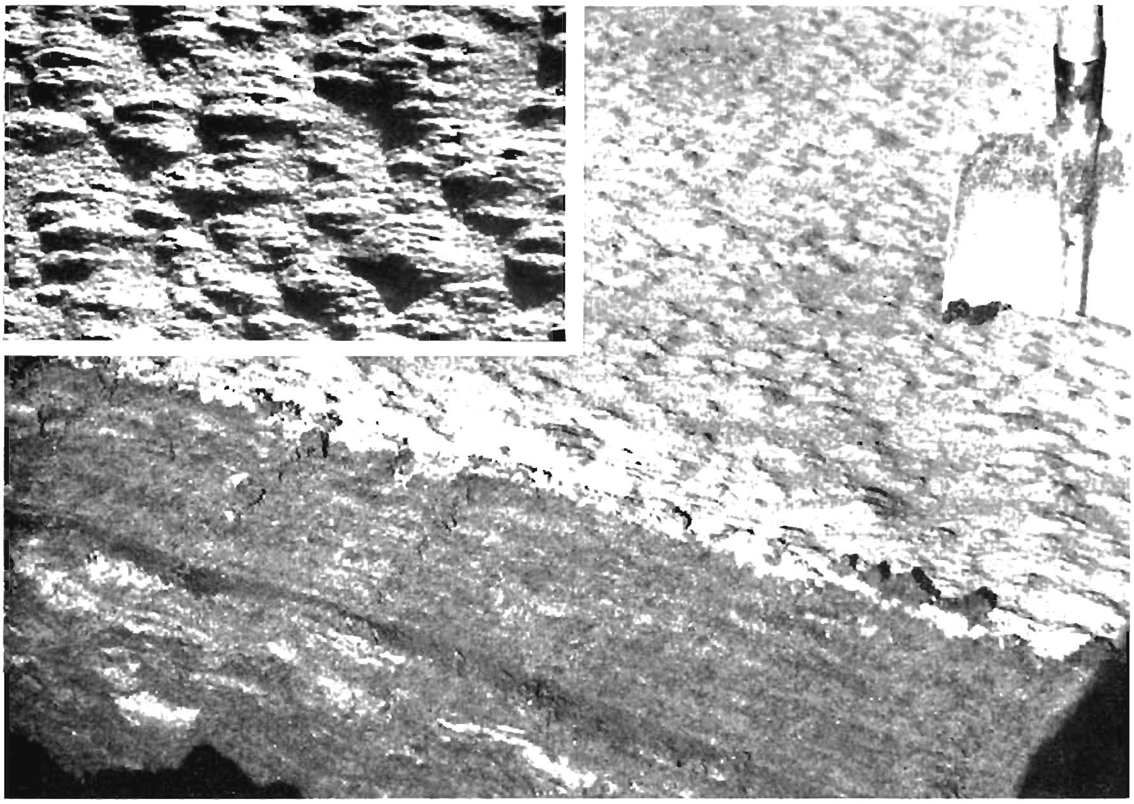

Figure 2A. Adhesion-ripple sand at locality 4. Continuous dark thin bed halfway through cross-section is probably due to reworking by an exceptionally high spring tide.

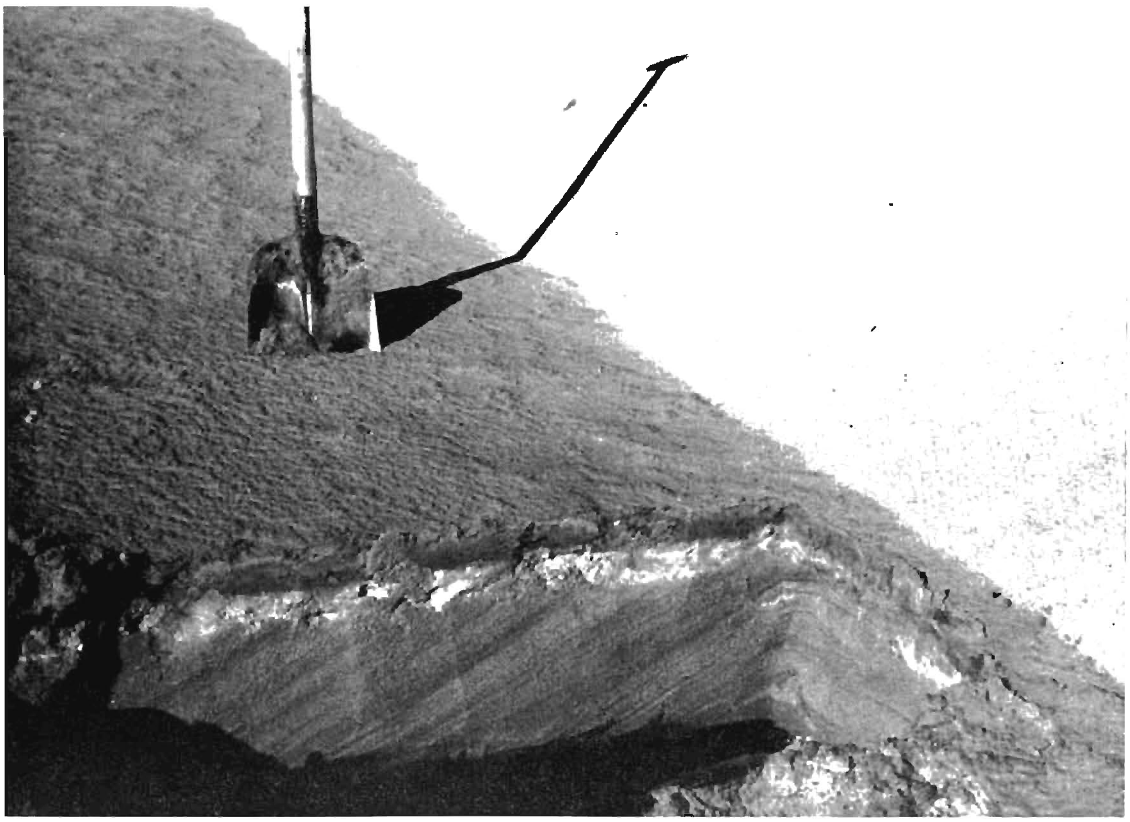

Figure 2B. Starting at bottom of hole: (1) dark silty clay, Kuiseb River deposit, (2) foresetted barchan-dune sand with halite crust (white) in top part, (3) thin bed of adhesion-ripple sand, (4) barchan dune, advancing from the right. Locality 5.

Table I. Characteristics of subsurface brines at localities 1-4

	Locality				Normal sea water
	1	2	3	4*	
Chloride Cl^-	89,8	92,6	99,5	99,4	19,0 gr/kg
Sulphate SO_4^{--}	5,6	8,2	8,8	10,3	2,6 gr/kg
Sodium Na^+	42,6	46,8	50,9	50,8	10,6 gr/kg
Potassium K^+	1,9	1,9	2,0	1,9	0,4 gr/kg
Magnesium Mg^{++}	5,3	5,9	6,5	6,7	1,3 gr/kg
Calcium Ca^{++}	0,6	0,7	0,8	0,9	0,4 gr/kg
Mg/Ca mol ratio	15,7	14,8	14,3	12,9	5,2
Density	1,117	1,124	1,133	1,134	1,024
pH	6,9	6,5	6,5	7,0	8,2
Eh (mV)	−20	+15	0	−21	

* Brine samples and pH-Eh measurements at 50 cm below supratidal sand-flat surface.

2. 3. Subsurface brines

Subsurface brines were collected at localities 1-4 (Fig. 1). The chlorinities of these sea-water-derived brines, and their SO_4^{--}, Na^+, K^+, Mg^{++} and Ca^{++} contents, are presented in Table I. A comparison of the chlorinities with that of normal sea water (Cl = 19,00‰) shows a concentration 4,7 (locality 1) to 5,2 times (localities 3 and 4) that of normal sea water. The densities of the brines increase from 1,117 at locality 1, to 1,134 at locality 4. An expected lower brine concentration at locality 4, due either to possible fresh-water influx from the Kuiseb River or to sea water in the lagoon (Fig. 1), is not evident from these data.

The brine concentrations exceed that at which precipitation of $CaCO_3$ and gypsum in sea water starts (3,35 times the concentration of sea water for gypsum; Philips, 1947). Both compounds are present as authigenic products in the sands. The brines have not reached the point of saturation for NaCl in sea water (at approx. ten times the concentration of sea water). Halite, however, is the most abundant authigenic mineral found on the supratidal flats, occurring in surface crusts. Because these crusts formed from capillary brines, it is evident that continued concentration takes place in the vadose zone.

The Mg/Ca ratio, three times that of normal sea water at locality 1, tends to decrease with distance from the coast; this is attributed to increasing dolomitisation of aragonite (p. 13).

The pH values measured in the brines are 1,2 to 1,7 pH units lower than that of open-sea water. This drop in pH value is thought to be due mainly to the release of CO_2 by the oxidation of organic matter which is present as small coprolites, and in other forms also.

The Eh values indicate neutral, weakly reducing, or weakly oxidising conditions. Oxidising conditions prevail above the water table, in the vadose zone. Here the sands are locally reddish-brown, due to surface coating of the sand grains with ferric oxides (Fig. 5). Below the water table, the sands are predominantly light grey. These data suggest that these recent supratidal sands do not necessarily lead to fully oxidised, reddish-brown deposits. This point is of interest, since many of the ancient Rotliegend adhesion-ripple sands (and the closely associated dune sands) are greyish in colour, in contrast to dune-sand sequences without adhesion ripples, which are commonly reddish-brown.

Table II. Petrographic composition of beach sand (3 samples), adhesion-ripple sand (4 samples) and barchan-dune sand (7 samples). Point-counting analyses, 500 points per thin section: average values shown

	Quartz	Chert	Feld-spars	Quartzite	Micas	Carbonate shell fragments	Heavy minerals	Copro-lites	Opaque grains + auth. Fe_2O_3	Auth. carbon-ates + sulphates
Beach sand	58,3	0,7	11,8	2,5	—	2,5	13,9	—	2,0	8,3
Adhesion-ripple sand	66,1	0,5	12,6	2,9	2,5	0,2	5,9	1,2	1,9	6,2
Barchan-dune sand	68,6	0,8	15,0	4,2	2,3	0,3	5,4	trace	3,3	trace

2.4. Clastic and authigenic constituents

The petrographic compositions of the three facies types of sand (the beach, adhesion-ripple and dune sands) are presented in Table II. The beach sands were sampled in the regressive sequence, from locality 1 to between localities 2 and 3. The adhesion-ripple sands are from localities 3, 4 and 5. The dune sands are from different parts of one barchan dune, at locality 5 (Fig. 1).

2.4.1. Clastic constituents

The analyses show that the sands are feldspar-rich quartz sands. The quartz grains are predominantly monocrystalline; 12,5% are polycrystalline. An estimated 70-80% of the grains show moderate to strong undulatory extinction. Among the feldspars, orthoclase, microcline and albite were noted; quartz/feldspar intergrowths were found in several cases. Minor quantities of chert and quartzite grains occur in all samples. No mica was found in the beach sands; this absence may be due to sorting processes. Biotite, a mineral typical of the Kuiseb River deposits, occurs in the adhesion-ripple sands collected at localities 4 and 5, and in the dune sands; a trace has been noted in the adhesion-ripple sand at locality 3. The carbonate fragments, many of them well-rounded pieces of pelecypod shells, were found mainly in the beach sands. Coprolites (a 0,5 cm aggregate of ovoid-shaped faecal pellets of unknown origin in one sample; a few single, similar pellets in others) were found in the adhesion-ripple sands; traces of this material occur in the dune sands.

Roundness

The quartz grains in the beach sands are predominantly subrounded, a smaller portion being subangular (roundness classes according to Pettijohn, 1956, p. 59). The adhesion-ripple sands contain varying amounts of angular grains (10-50%; estimated), the remainder being made up mainly of subangular to subrounded grains, with a few that are rounded to even well-rounded. As regards roundness, the dune sands are similar to the adhesion-ripple sands, but the content of fully-angular grains is less variable and generally exceeds 30% (estimate). Virtually all grains in the dune of less than 0,2 mm diameter are angular; angular grains in this size range are exceptional in the beach sands.

The presence of appreciable quantities of angular, rounded and well-rounded grains in the adhesion-ripple and dune sands is a striking feature. This fact suggests a clastic-supply influence from the Kuiseb River sands, which contain the peculiar assemblage of angular and rounded to well-rounded grains*.

* Due to fluvial supply to the Kuiseb of angular quartz from basement rocks (granites, metamorphics) and eolian supply of rounded to well-rounded quartz from the large seif dune field south of the river.

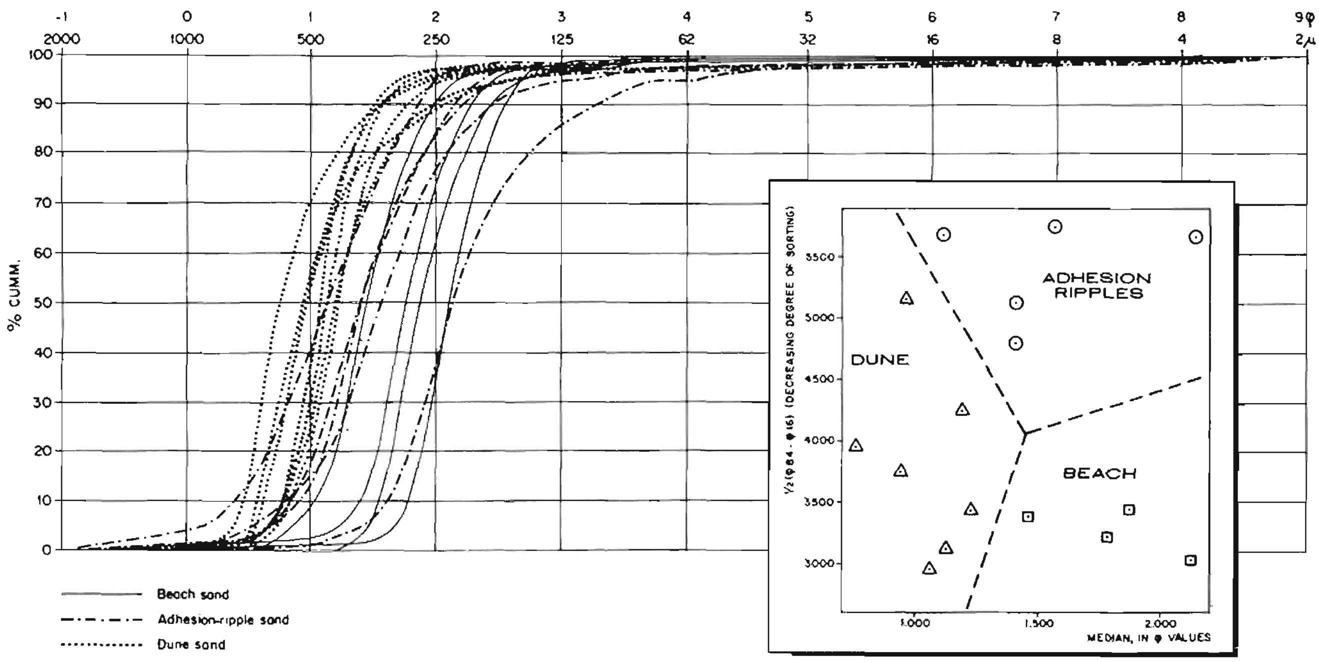

Figure 3. Namib Desert coastal deposits; grain-size characteristics of beach, adhesion-ripple and barchan-dune sands.

Grain size

The grain-size analyses of the three types of sand are shown in Figures 3A and B. The three types of sand separate into different fields in a plot of median diameter against sorting [in φ values, using $^1/_2$ $(\varphi\,\varphi_{84-16})$ as a measure of sorting; Inman, 1952]. The beach sands have the finest grain size (average median value, 289 micron) and show the narrowest spread in sorting. The barchan-dune sands, on the other hand, are much coarser (average median value, 488 micron) and show a wide range in sorting. The adhesion-ripple sands occupy an intermediate position as regards grain size (average median value, 355 micron), but show the lowest degree of sorting.

The maximum grain size encountered in the beach sands falls in the 700-900 micron range (in one of the four samples analysed; the others: 500-600, 450-500 and 350-400 micron). The maximum grain size in the adhesion-ripple sands is in the 1000-2000 micron range [in one sample of five; the others: 900-1000 (2), 700-900 (1) and 500-600 micron (1)]. The dune-sand samples (1) have maximum grain sizes in the 700-900 micron range.

On the basis of these data, it would be impossible for the adhesion-ripple sands to be derived entirely from the beach sands. The dune sands, however, could have been derived from them. In view of the mineralogical and roundness data, which suggest an influence from the Kuiseb River sands, this latter possibility seems unlikely (p. 11, p. 12). The larger grains in the adhesion-ripple sands could well originate from the Kuiseb River. It should be realised, however, that the number of samples is small and that coarser beach sands may also occur.

Heavy minerals

Analyses of the heavy-mineral content of Kuiseb River sands (four samples, collected between the artificial dam, and Gobabeb, 45 km southeast of the dam, Fig. 1), dune, adhesion-ripple, and beach sands show that the same heavy minerals are common to all four types of sand; no heavy-mineral species are restricted to any one of the sand types. The assemblages are characterised by a high sillimanite content, and by the presence of garnet and hornblende (blue-green variety), which, together with the presence of staurolite, kyanite, andalusite and epidote, indicates a source composed of high-rank metamorphic rocks (Fig. 4; average values shown). This source can only be the Pre-Cambrian basement, which occupies the greater part of the Namib Desert, probably including the areas covered by dune sands and other surficial deposits.

Heavy-mineral counts for the beach sands clearly show a very high sillimanite, and relatively low garnet and hornblende, content. The Kuiseb sands are much richer in garnet and hornblende, but still contain an appreciable amount of sillimanite. The

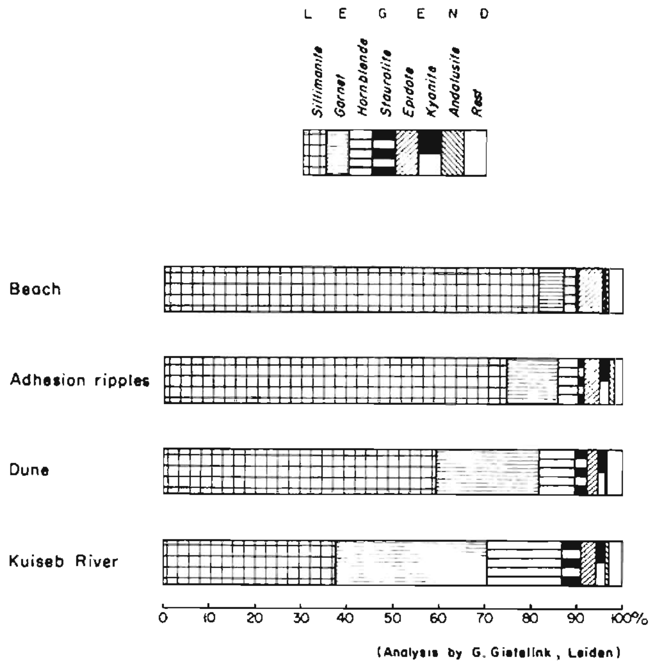

Figure 4. Frequencies of heavy minerals in Kuiseb River, dune, adhesion-ripple, and beach sands.

dune and adhesion-ripple sands are intermediate with respect to the abundance of these minerals (Fig. 4). Apart from the heavy minerals mentioned, zircon, rutile, zoisite and cordierite also occur, but each with a frequency of less than 2%; in Figure 4 they have been grouped collectively as the 'rest'.

In all four types of sand, the majority of the heavy minerals, including the major component sillimanite, fall in the 100-250 micron grain-size range. However, maximum grain sizes (commonly hornblende and garnet) are in the 1-2 mm range for the Kuiseb River, dune and adhesion-ripple sands; the beach sands contain no heavy-mineral grains larger than 700 micron. These data suggest that the proportional differences displayed by the heavy-mineral assemblages are at least in part a grain-size effect, and therefore need not indicate different sources (Fig. 4). However, the same roundness differences as found for the quartz grains (p. 11) also occur in the heavy-mineral fractions. In the beach sands, nearly all heavy-mineral fractions are rounded to well-rounded; angular to subangular garnet, hornblende and staurolite, both in the fine and in the coarse grades, occur together with rounded to well-rounded grains in the other sands.

As with the quartz grains, it is thought that these angular to subangular grains originate from the local basement rocks, are first transported by the Kuiseb River, and then accumulate by means of wind action in the dunes and adhesion-ripple sands. More detailed sampling and heavy-mineral analyses of separate grain-size fractions are needed to show whether or not the dune and adhesion-ripple sands are mixtures of Kuiseb River and beach sands.

2.4.2. Authigenic constituents

Authigenic aragonite, high-magnesian calcite, calcian dolomite, gypsum, bassanite, and halite have been observed both in thin sections and in X-ray diffractograms of samples from the supratidal-sand-flat deposits. Authigenic ferric oxide was noted only in the thin sections; it occurs in quantities too small to be recorded in the < 53 micron fraction (dry sieving) samples prepared for the diffractometer.

Ferric oxide is the first to form. In thin sections of the reddish-brown stained parts of the adhesion-ripple sands, it occurs as thin coatings on most grains (Fig. 5B). The ferric-oxide coatings are thickest in the immediate vicinity of decomposed and partly disintegrated opaque grains. The coatings apparently stem from such grains, the original composition of which has yet to be investigated.

Taken together, the authigenic carbonates and sulphates content averages 8,3% of total rock volume in the beach sands and 6,2% in the adhesion-ripple sands, while only traces occur in the dune-sand samples (Table II). The true averages for the first two sand types will be lower, however, because the most strongly cemented parts were usually sampled. Cementation with halite is concentrated in thin (a few centimetres thick) surface crusts, best developed in the adhesion-ripple sands. The X-ray diffractograms show that halite also occurs in all dune-sand samples. At the base of the dune, the halite probably crystallised from capillary brines; higher in the dune, however, it may well have been incorporated in the sand by wind action. Carbonates and sulphates occupy up to 12% of the rock volume. In these cases the sand grains are fairly strongly bonded (not easily broken by hand), the sand showing a surface expression of polygons 1-2 m in diameter.

Authigenic high-magnesian calcite (17-20 mol% $MgCO_3$) was found in beach-sand samples taken from localities 1 and 2. The absence of any signs of corrosion by waves suggests that these beach sands cemented with high-magnesian calcite are not beach rock (which forms in the intertidal zone; Ginsburg, 1953; Alexandersson, 1969), but formed on the landward side of the beach barrier. Calcian dolomite (molar composition between Ca_{55} Mg_{45}-Ca_{51} Mg_{49}) occurs in adhesion-ripple sands from localities 3 and 4. Gypsum and bassanite are irregularly distributed. Both minerals occur in appreciable quantities at locality 4, while only traces were noted at the other localities. No anhydrite has been found. Aragonite was found only at locality 3; it occurs there in concentric, radiated aggregates (Fig. 5A). The high-magnesian-calcite and calcian-dolomite crystals are extremely small, not exceeding 4 micron; the aragonite aggregates measure up to 150 micron. The delicate structure of the aragonite is locally destroyed by swarms of the much finer grained, calcian-dolomite crystals, and this is taken as evidence of dolomitisation of the aragonite. The gypsum and bassanite form radiated aggregates of slender crystals up to 1 mm in size; locally, both minerals are densely intergrown.

The distribution of the authigenic carbonates in the sands is typically that shown in Figure 5B. The minerals concentrate at the grain contacts and form coatings on grain surfaces, thinning away from these contacts. Gypsum, bassanite and halite also occur preferentially at or very near to grain contacts. At several places in the thin sections, cementation has progressed much further than shown in Figure 5B. In such cases, thick crusts line the pore walls, leaving only a small central void.

The characteristic distribution of the authigenic minerals is explained as being the result of crystallisation from capillary brines, which show a similar distribution in the vadose zone. It may therefore be concluded that, in the present supratidal-flat sands, appreciable cementation takes place in the vadose zone. Dolomitisation of the aragonite probably occurs here as well. All our sand samples were collected from the vadose zone. However, the concentration and composition of the brines below the water table are such that precipitation of aragonite and gypsum should also have occurred; dolomitisation can also be expected there.

The type of early diagenesis on the supratidal sand flat at Walvis Bay is essentially similar to that recorded from coastal sabkhas along the Trucial Coast (Illing et al., 1965; Kinsman, 1969). This demonstrates the importance of the two major environmental factors that both types of area have in common, a hot arid climate and the geomorphic setting. The difference between the areas lies only in the composition of the clastics; i.e. quartz sands at Walvis Bay and predominantly carbonate material along the Trucial Coast.

3. THE ROTLIEGEND DESERT, NW EUROPE

3.1. Geomorphic and climatic setting

Near the end of the Carboniferous, two major changes occurred in NW Europe: mountain ranges formed from the Variscan geosynclines, so determining the geomorphic setting for the subsequent deposition, and the climate changed from humid to semi-arid and hot arid. This aridity was the main cause of the red colouration in the post-orogenic continental deposits.

As the final result of the Variscan orogenic developments, during the Carboniferous/Permian transition, major parts of W. Germany, The Netherlands, Belgium and Great Britain were occupied by mountain ranges (Variscan Mountains, Brabant Highlands, St. George's Land, the Pennines), while low-relief forelands extended to the north, into the present North-Sea area (Kukuk, 1938; Brinkmann, 1959).

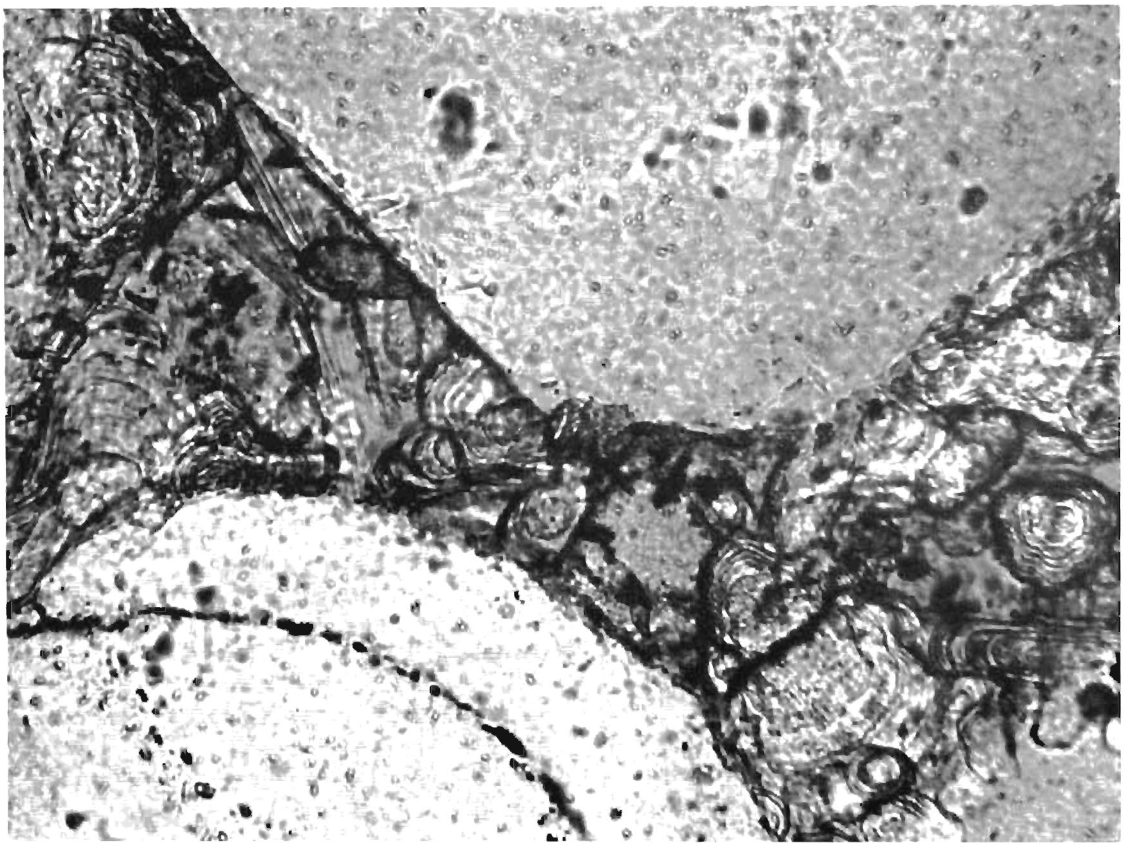

Figure 5A. Concentric, radiated crystal aggregate of aragonite, intergrown with gypsum (fibrous, lower right-hand corner), newly formed between two quartz grains. Locality 3. Long edge of micrograph corresponds to 0.2 mm

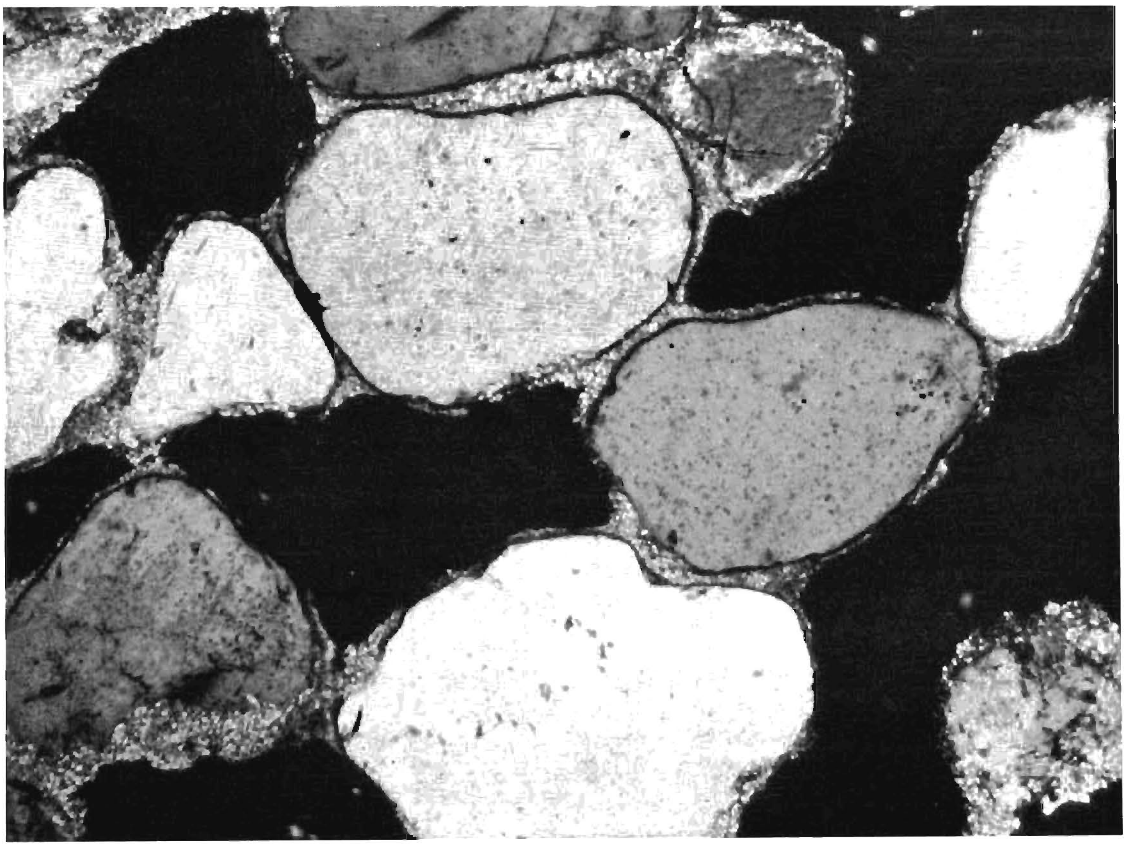

Figure 5B. Fine-grained, authigenic calcian dolomite concentrated at grain contacts and as thin coatings. Dark, thin, ferric-iron coating directly on grain surfaces. Long edge of micrograph corresponds to 0,6 mm.

The Late-Paleozoic change in climate is well-recorded in a number of complete depositional sequences found in the Plateau Central in France (Kruseman, 1967) and in the Spanish Pyrenees (Nagtegaal, 1969). In the area that will presently be discussed, the south-central part of the North Sea, the uppermost Carboniferous (Stephanian) is generally absent, and the Rotliegend then directly overlies the paralic, coal-bearing Westphalian strata.

3.2. Desert deposits

The Rotliegend in NW Europe is developed in two main facies types; (i) a more than 1500 km long (generally 250 km wide, and 200-300 m thick), east-west oriented sheet of predominantly sands and conglomerates, which largely formed on the north side of the Variscan mountain ranges, and (ii) an adjacent shale to shale/salt sequence, the so-called 'Haselgebirge facies', up to 1000 m thick.

The extent of this latter facies type under the central part of the North Sea is not yet fully known. The evaporites in the Haselgebirge facies consist of halite, which is almost free from the commonly associated carbonates and sulphates. Richter-Bernburg (1953) explained this evaporite composition as due to precipitation from sea water which had lost its carbonates and sulphates in a previous stage of evaporation. Brunstrom and Walmsley (1969) suggested that the evaporites were deposited in a large inland basin, the rock salt being derived fluvially from assumed piercement structures of Devonian evaporites.

The sands and conglomerates, which are predominantly reddish-brown in colour, are interpreted as having accumulated in a desert environment. This conclusion is based mainly on the fact that the extensive sand deposits, which were interpreted as fossil transverse and barchan-dune fields, formed in association with the adjoining evaporites (Shotton, 1956).

There are many similarities between the Rotliegend and recent desert deposits; the most significant of these are the occurrence of (a) ephemeral stream ('wadi') deposits, often containing intercalated eolian sands, (b) dune sands, (c) adhesion-ripple sands, (d) numerous smaller sedimentary structures such as sand dykes, mud-cracks, and flat clay pebbles which are assumed to have been derived from mud-cracked horizons.

In several localities, the Rotliegend ephemeral stream deposits coalesce into alluvial-fan complexes with northwards transport (away from the Variscan highs, see above). The foresetting in the dune sands indicates the prevalence of winds from the east (Shotton, 1956; Laming, 1966). The adhesion-ripple sands are interbedded with dune sands. They occur in areas of transition between the main sand sheet and the evaporite basin. For a general discussion of these various types of deposits, reference is made to Glennie (1972). In the present text, attention is directed to the sequences composed of interbedded adhesion-ripple and dune sands, comparing them to the coastal Namib deposits discussed in the previous section.

3.3. Adhesion-ripple/dune-sand sequences

Sequences of interbedded adhesion-ripple and dune sands have been studied in the cores of two wells drilled in the south-central part of the North Sea. In one core the sequence is developed over a total thickness of 120m; in the other over a total thickness of 90m. In both cases the sequences are underlain by dune sands and ephemeral stream deposits, and are overlain by dune sands without adhesion-ripple intercalations.

3.3.1. Sedimentary structure

Five photographs of representative core parts are shown in Figure 6. Adhesion ripples can be seen in Figures 6A, B and C. The irregular lenticular structure is similar in size and shape to that observed in the recent adhesion-ripple sand at Walvis Bay (Fig. 2A). The geometric relationships with the foresetted dune sands (dune sand on top of the adhesion-ripple sands shown in Fig. 6A, and below them in Fig. 6C) are also seen in the recent deposits (Fig. 2B). In Figure 6B, the adhesion-ripple sands are overlain by horizontally-laminated sands. These laminated sands (present also in Figs. 6D and E) commonly shown bimodal grain-size distributions, visible in thin section as alternating coarse- and fine-grained laminae. Although the parallel structure is similar to that found in beach sands, the characteristic bimodal distribution makes such deposition unlikely. These sands are interpreted rather as having been wind-deposited on wide, flat surfaces (Folk, 1968). In the present case, the gradual development from adhesion-ripple sand to overlying, parallel-laminated, bimodal sand probably indicates either (a) a falling water table, or (b) a sudden increase in the amount of sand supplied. In this interpretation, the parallel-laminated sands were deposited above the level of capillary moisture and vadose cementation.

In the total sample investigated, 59% of all dune-sand beds contain a foreset structure corresponding to a single dune (no deflation surfaces present). In the remaining 41% of the dune-sand beds, 1 to 4 deflation surfaces occur per dune-sand bed. Wherever a deflation plane is horizontal (i.e. in the majority of cases), a break in grain size occurs, the sand directly overlying the deflation surface being coarser grained than that just below it. Such a relationship is thought to imply the presence of sand from two separate dunes. In other cases (no horizontal position, no break in grain size), the deflation surfaces were probably formed in one

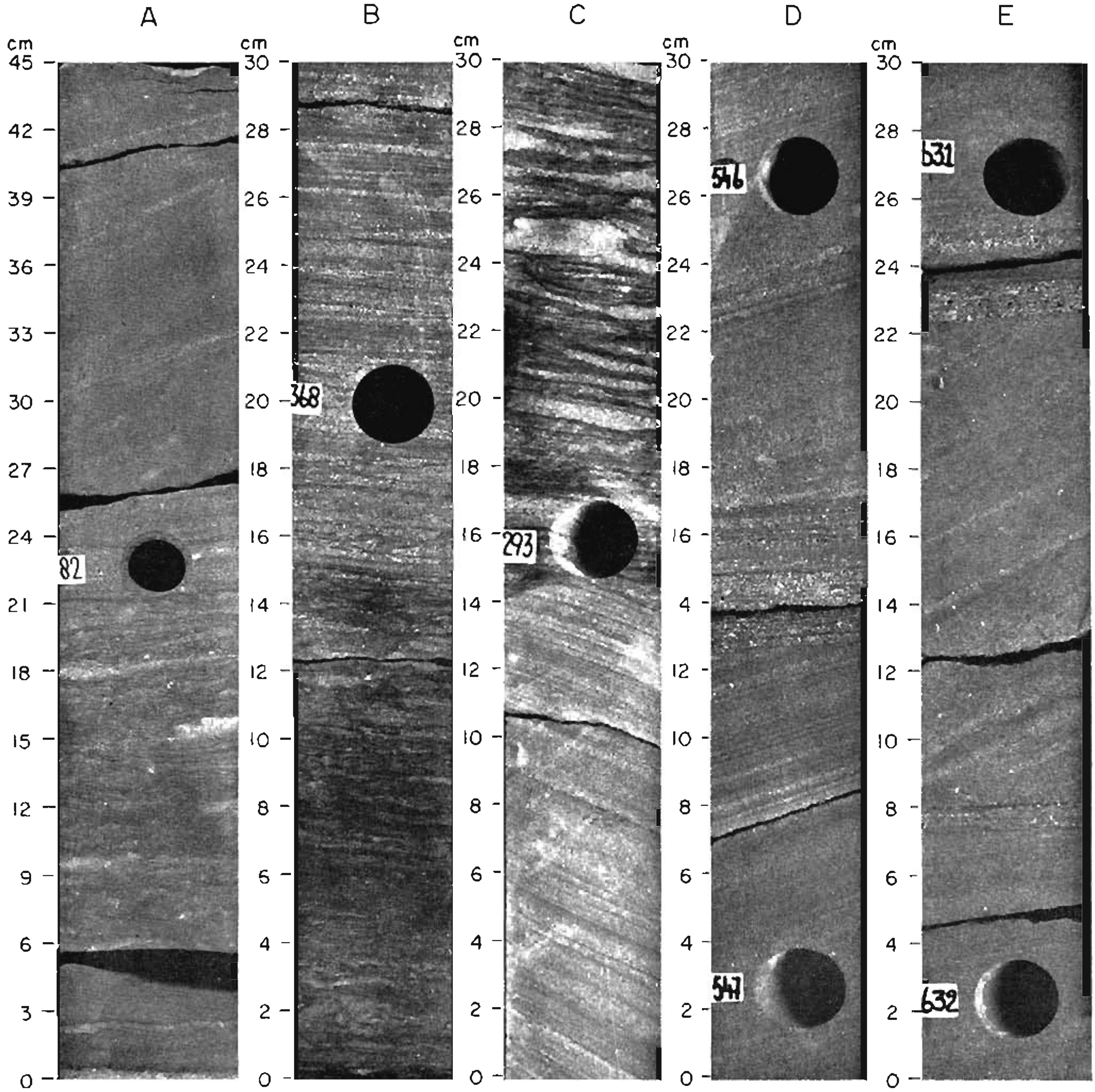

Figure 6. Representative eolian sand sequences in the Upper Rotliegend desert deposits: (A) dune sand overlying adhesion-ripple sand, (B) parallel-laminated bimodal sand overlying adhesion-ripple sand, (C) truncated dune sand, showing small 'ridge', overlain by adhesion-ripple sand, (D, E) dune sands and parallel-laminated, bimodal interdune sands.

dune as a result of changes in wind direction and wind strength. Examples of multiple dune-sand beds are shown in Figures 6D and E. No such multiple dune-sand beds have been observed at Walvis Bay, but dunes migrating directly over surfaces representing truncated barchan dunes do occur. Without exception, the upper bedding planes of dune sands are deflation surfaces, no complete dunes having been observed.

Almost all bedding planes in the cores investigated are subparallel, suggesting an essentially parallel-bedded sequence of sediment. In some cores (e.g. Fig. 6C), minor culminations occur on the upper surface of dune sand in contact with overlying adhesion-ripple sand. These culminations are comparable in size and location to the curved ridges found in the recent deposits (p. 8). The foresets of the dune sands shown in Figure 6 make angles of 18-24° with the horizontal, which are smaller than the angles made by barchan-dune foresets at the surface (32-34°). These lower angles result both from the fact that the cores shown in Figure 6 have not been cut exactly perpendicular to the strike of the foresetting, and from compaction during the burial history of the deposits, which is estimated at approximately 20% of the total initial sand volume.

3.3.2. Composition

The Rotliegend sandstones are similar in composition to the Namib sands, being feldspar-rich quartz sandstones. Authigenic minerals include dolomite, anhydrite, K-feldspars, quartz, and clay minerals. The first three components are of interest in the present context. The authigenic dolomite can be differentiated into a non-ferroan type, which crystallised first, and a ferroan type which formed later. The distribution of the non-ferroan type of dolomite in thin section is in many instances identical to that for the recent dolomite (Fig. 5B), although its crystal size is much larger; it occurs preferentially at grain contacts. The same applies to some of the anhydrite, which suggests early cementation in the vadose zone. This indicates that, in the Rotliegend deposits, as in those of the recent Namib, concentrated brines occurred just below the surface.

Authigenic K-feldspars (overgrowths) are present in almost every thin section of Rotliegend sandstone. They are thought to have been formed relatively early; in all observed cases, prior to the formation of quartz overgrowths. This suggests a relationship with the Upper Rotliegend desert environment, the concentrated brines of which may have formed a favourable *milieu* for the generation of K-feldspar (Hay, 1964). No authigenic K-feldspars were found in the recent Namib sands.

3.3.3. Grain size

The grain-size data for the Rotliegend sands (Fig. 7) should be regarded as approximate, both because the samples are cemented sandstones which had to be carefully crushed before analysis, and because the presence of insoluble authigenic minerals has an influence on the grain-size distribution.

The Rotliegend sands on the whole are finer-grained and more poorly sorted than the same types of Namib sands (Fig. 3). Although there is a considerable spread in the data, the same relative differences are found; the adhesion-ripple sands are both finer-grained and more poorly sorted than the dune sands.

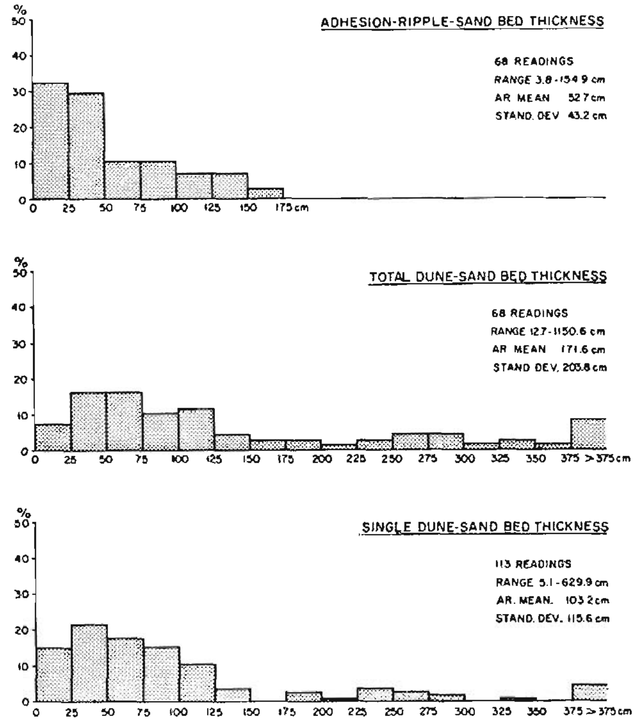

Figure 8. Frequency distributions of adhesion-ripple, total-dune, and single-dune sand-bed thicknesses.

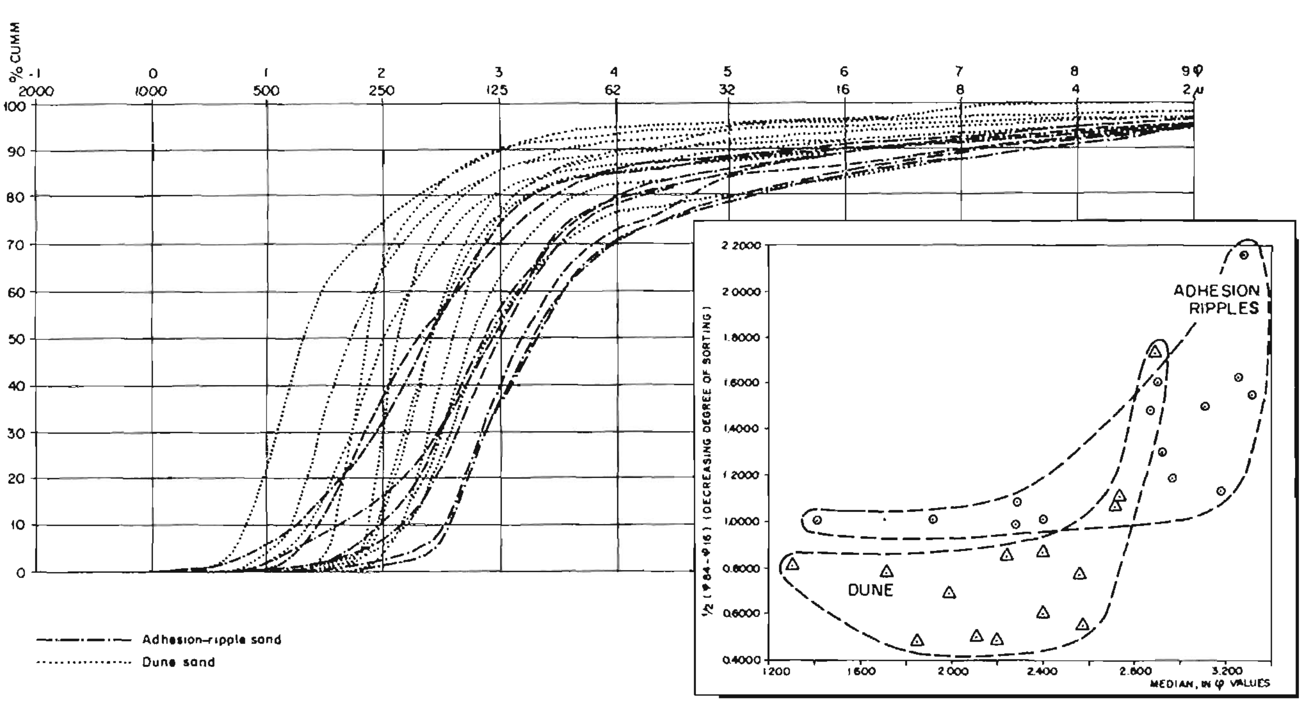

Figure 7. Upper Rotliegend desert deposits. Grain-size characteristics of adhesion-ripple and dune sands.

3.3.4. Bed-thickness, environmental implications

The results of bed-thickness analyses are shown, in the form of histograms, in Figure 8. The least spread in thicknesses is found in the case of the adhesion-ripple sands; the widest spread occurs in the case of the totally dune-sand intervals. The majority of the Rotliegend adhesion-ripple sand-bed thicknesses falls in the range displayed by their recent equivalents (more than 82% are between 4 and 100 cm thick; p. 8).

When the total dune-sand intervals are split into their constituent single dune-sand beds, and the frequency distribution for all single-dune-sand beds is computed, the majority (83%) of the beds are found to cluster between 5 and 150 cm. This fits the order of magnitude of the thicknesses displayed by the dune-sand beds in the Namib Desert (p. 8), and it is therefore possible that the same process of dune-base cementation with mainly halite proceeded in the Rotliegend desert deposits. Except for the occasional small ridges (p. 16, Fig. 6C) and the overall similarity in sedimentary structures, no evidence for the occurrence of surface halite cementation has been found in the Rotliegend deposits. However, if halite crusts did develop in Rotliegend deposits, they can hardly be expected to have been preserved. In these deposits the halite would have been dissolved by the rising groundwater; it may have reprecipitated at the surface or may have been redistributed otherwise. There therefore appears to be no direct way of determining how important surface halite cementatation was in the Rotliegend deposits.

Dune-sand/adhesion-ripple-sand ratios fluctuate in a more or less regular pattern about a mean value when plotted against the lengths of the cores analysed; no general trend of increasing dune-sand content, or of bed thicknesses, could be detected in either an upward or a downward direction. An almost completely random relationship appears to exist between the thicknesses of dune-sand beds and those of the directly overlying and underlying adhesion-ripple beds. The correlation coefficient computed for the relationship with the overlying adhesion-ripple beds is 0,00901; for that with the underlying beds it is 0,01458. The above facts suggest that, over the total lengths of core analysed, the environment essentially remained in a delicately-balanced equilibrium with probably wide, low-lying plains having near-surface ground water tables, over which migration of swarms of transverse dunes occurred. It also follows that the rate of accumulation must have been closely attuned to the rate of subsidence.

4. CONCLUSIONS

1. The sedimentary structure of beds of adhesion-ripple and barchan-dune sands now forming in the coastal area of the Namib Desert is similar to that found in a wide belt of Rotliegend sandstones in the North Sea Basin. The main environmental factors are: (a) geomorphic setting (wide, low-lying plains, groundwater at shallow depths below the surface), and (b) a desert climate.

   However, the similarity between the main environmental factors does not necessarily imply that the geographic positions were entirely the same. The Namib deposits form on a coastal plain directly bordering the ocean; the Rotliegend deposits investigated accumulated on low-lying plains which were located some tens of kilometres from the (probably strongly fluctuating) coastline of the Haselgebirge saline lake or landlocked sea.
2. At and near-surface precipitation of mainly halite plays a part in (a) preservation from deflation of earlier deposited sands, and (b) the formation of parallel-bedded sequences of alternating adhesion-ripple and foresetted dune sands.
3. Early diagenetic (vadose zone) precipitation of $CaCO_3$, calcium sulphates and dolomitisation, observed in the Namib Desert deposits, probably also occurred in the Rotliegend sands.

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