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LACUSTRINE SEDIMENTS AT NARABEB IN THE CENTRAL NAMIB DESERT, NAMIBIA

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ABSTRACT

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Deep within the hyper-arid Namib Desert at Narabeb, which is today isolated by 100-m high linear dunes, is a 36-m section of lacustrine mudstones and interbedded sands. The slightly calcareous and laminated sands of this sequence are composed mainly of rounded to subrounded, lightly stained quartz that is similar to the sands of the underlying Tertiary Tsondab Sandstone Formation and the surrounding dunes of the Namib Sand Sea. The six calcareous mudstone units in this sequence are variably laminated and sandy, contain halite-filled fractures, and have been radiocarbon dated at 20,000—26,000 yr B.P. The interrelationship of sediments at this site with Middle to Early Stone Age implements suggests an age of more than 20,000 years, whereas $^{234}U/^{230}Th$ dating of the basal mudstone gave an age of 210,000—260,000 yr B.P.

The calcareous mudstones were deposited in a lake at the former end point of the Tsondab River, which was prevented from reaching the Atlantic Ocean by N—S trending linear dunes of the Namib Sand Sea. The interbedded sands were deposited during low water or dry stages of the lake. Sometime before 14,000 yr B.P. the terminus of the Tsondab River shifted eastward from Narabeb in response to the northward encroachment of linear dunes, and the present end point was eventually established at Tsondab Vlei, 38 km to the east. Lacustrine deposition at Narabeb, just as at Tsondab Vlei today, probably occurred mainly in response to precipitation in the headwaters of the Tsondab River. Although no major climatic change is necessary to explain the sequence at Narabeb, the clustering of radiocarbon dates on carbonate from the Namib Desert in the periods 20,000—35,000 yr B.P. and 10,000—14,000 yr B.P. suggests an increase in precipitation during those times.

INTRODUCTION

The Namib Desert is a narrow region along the western coast of southern Africa that extends about 2000 km from the Olifants River in South Africa

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northward to the Carunjamba River in southern Angola (Ward et al., 1983). It lies west of the Great Escarpment in Namibia, which parallels the coast 100—200 km inland (Fig.1). Although this coastal desert is arid to hyper-arid, there are a variety of modern depositional settings that overlie the Late Cretaceous pediplaned bedrock surface, ranging from coastal salt flats to inselberg-dotted barren bedrock that is veneered by a thin mantle of gravel

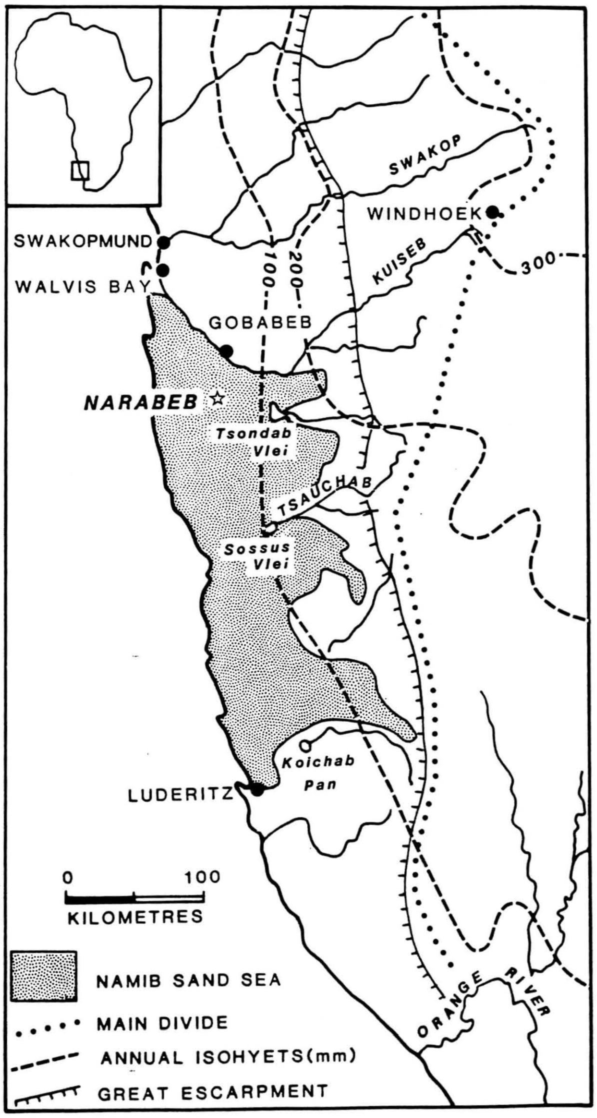

Fig.1. Map showing location of Narabeb in the Namib Sand Sea. Also shown are major river courses that drain from the Great Escarpment toward the Atlantic Ocean and precipitation isohyets (modified from Marker, 1977).

and grus, to the Namib Sand Sea in the central regions, where some of the largest linear dunes in the world are found. Several rivers head in the uplands to the east and cut across the desert to the Atlantic Ocean. The Sand Sea is bounded on the north by one of these rivers, the Kuiseb (Fig.1).

As discussed by Ward et al. (1983), the origin and long history of the Namib Desert is not well known. The cold northward-flowing Benguela Current was established following the break-up of West Gondwana and establishment of the South Atlantic Ocean, providing a mechanism for the increasing aridity in this coastal region during the early Tertiary (Van Zinderen Bakker, 1975). Siesser (1980) and others, however, believe that this current did not become fully established until Late Miocene time.

The Tertiary sedimentary record in the Namib Desert is scattered. Fluctuating sealevels and climates have resulted in a complex pattern of marine, fluvial, and aeolian deposits that have a variety of erosion surfaces, palaeosols, and calcretes developed in them (Ward et al., 1983). The age relationships of these deposits are not well understood, but the record suggests a climate that may have fluctuated from hyper-arid to arid, and possibly to semi-arid. Ward et al. (1983), however, caution that conclusions about the existence of wetter climatic conditions at any time during the Cenozoic, based on scattered biological remains or sediments, should be tempered with the knowledge that, even in today's hyper-arid Namib Desert, river courses and pans support a community of water-demanding organisms and may leave sediments similar to those in much wetter regions. The fact that most modern and ancient rivers of the Namib head to the east in areas of higher rainfall means that conditions along these watercourses may not reflect the climate of the Namib Desert.

The Namib Sand Sea (Fig.1) probably originated in the Pliocene (Ward et al., 1983), rather than in the Pleistocene as Martin (1973), Tankard and Rogers (1978), and others have proposed. The sands of this desert were derived from the southern coastal area (Lancaster, N. and Ollier, 1983), which receives most of its sediment from the Orange River (Rogers, 1977), with probable contributions from the older Tertiary clastics in the region (Besler and Marker, 1979). Evidence for an Early to Middle Tertiary age for aeolian sands in the southern and central part of the Namib has been summarized by Ward et al. (1983). Most investigators feel that prevailing southerly winds have progressively, albeit erratically, pushed the edge of the Namib Sand Sea northward (Wienecke and Rust, 1972; Ollier, 1977; Ward, 1982). The present northern boundary, which lies at the Kuiseb River valley, probably had been established by Early to Middle Pleistocene time (cf. Ward, 1982).

The linear dunes of the Namib Sand Sea are among the largest in the world. Their dimensions, grain-size, characteristics, and origin have been discussed by Lancaster, N. (1983). Dunes are elongated in a N—S direction, spaced 1200—2800 m apart, and rise from 30 to more than 150 m above interdune troughs. Transverse, barchanoid, and star dunes comprise less than 25% of the dunes in the Sand Sea.

HYDROLOGICAL SETTING

The climate of the central Namib Desert is extremely arid and warm, with mean monthly temperatures ranging between 17°C and 24.5°C. Records at Narabeb (Fig.1) indicate that rainfall varies from 0 to 25 mm annually, with an average of 20.4 mm. Fog precipitation adds another 36 mm each year (Lancaster, J. et al., 1984). Rainfall gradually increases toward the east, and above the Great Escarpment in the central Namib averages 200—300 mm per year (Fig.1). As a result, rivers such as the Tsondab, Tsauchab, and Koichab, which flow from the wetter eastern regions and terminate in the Sand Sea, as well as those that are able to maintain a course to the Atlantic Ocean such as the Kuiseb River, owe nearly all of their flow to rainfall events that occur only in their distant headwater reaches. Although flow in the largest of these rivers, the Kuiseb, occurs in its headwaters every year, it reaches the ocean on an average of only every eight years (Stengel, 1964).

The Narabeb site is isolated today by linear dunes that rise nearly 100 m on both the eastern and western sides of the 2—2.5-km wide interdune corridor in which the lacustrine deposits are found. To the east, toward the Great Escarpment from which most runoff into the Namib Sand Sea comes today, are a series of N—S linear dunes that further isolate the Narabeb site. There is no evidence of standing water or flow through this depression in recent times. Tsondab Vlei, which lies at the terminus of the small (3640 km^2) catchment of the Tsondab River, 38 km to the east of Narabeb, only receives runoff on rare occasions (Stengel, 1970).

DESCRIPTION OF SEDIMENTS AT NARABEB

Introduction

Deposits in the interdune corridor at Narabeb lie at 23°49′S and 14°57′E, 47 km inland from the Atlantic coast and 34 km south of the Kuiseb River channel, which forms the northern border of the Namib Sand Sea (Fig.1). The 36-m thick section of sediments (Fig.2), first noted by Seely and Sandelowsky (1974), is exposed for about a kilometer along the eastern side of this N—S corridor between linear dunes that rise nearly 100 m above the interdune floor. This sequence is composed of sands and calcareous mudstones, and rises to a "bench" along the flank of the linear dune (Fig.2). It overlies Tertiary Tsondab Sandstone, which forms the floor between many of the dunes in this area.

A summary of the properties of each of the 11 units in the section is given in Table I; Teller and Lancaster (in press) provide a detailed description.

Although the upper third of the section contrasts with the lower part, in that it is uniformly high in sand content, it is distinct from the modern aeolian sand that rises above its upper "bench" surface in being cohesive enough to maintain a slightly oversteepened face (Fig.2). This sequence also

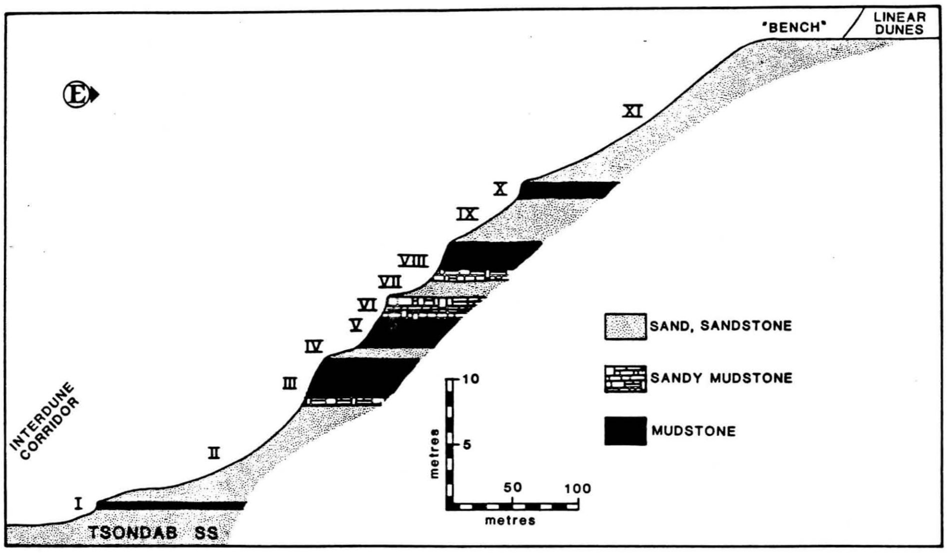

Fig.2. Schematic cross section of sediments at Narabeb. See Tables I and II for details.

contrasts with the underlying Tsondab Sandstone, which has a more distinct red colour (5 YR 5/8, yellowish red) and is more tightly cemented. On aerial photographs, the calcareous part of the sequence stands out as a light-toned band.

Sand units

Quartz is by far the dominant mineral in all sand units. Albite, dark minerals such as augite, garnet (almandine), together with quartzite, make up less than 10% of the remainder of the clastic grains. Up to 7% finely disseminated calcite occurs in these sand units. The average grain size of all of the sand units interbedded with the calcareous mudstones is fine to very fine sand, whereas that of the thick upper part of the sequence is medium-grained sand. Sorting ranges from moderately well-sorted to moderately sorted. An analysis of the underlying Tsondab Sandstone indicates that it is well sorted at Narabeb, although Besler and Marker (1979) characterize the sandstone elsewhere as moderately to poorly sorted. Nearly all clastic grains in the Narabeb sequence are subrounded to well rounded. Darker-stained quartz grains, augite, quartzite, and other rock fragments tend to be better rounded than the amber coloured quartz grains that make up the bulk of the sand units. The percentage of frosted (pitted) grains increases upward in the section, with most quartz in the uppermost unit being frosted. Few grains in the underlying Tsondab Sandstone appear frosted, but they have a distinctive vitreous patina on their surface; Besler and Marker (1979) made a similar observation for the Tsondab Sandstone Formation elsewhere. Virtually all

TABLE I

Summary of characteristics of each unit ar Narabeb

Unit	Thickness (m)	Lithology[a]		Insoluble residue[b]			HCl sol.	Sand stats.[c]		Clay mineralogy[d]				Bulk-mineral X-ray and microscopic analyses[e]					
				Sand	Silt	Clay		Mean size	Std. dev.	I	Ex	K	C	Qtz	Alb	Dar	Mic	Cal	Hal
XI	11.0	Sand	L	100	0	0	0	1.7	0.51					+	—	—		—	
X	1.1	Mudstone		5	36	59	41			45	33	13	9	+	—	—		+	—
IX	3.6	Sand		98	2	0	7	2.6	0.53					+	—	—		—	
VIII	2.8	Mudstone	U	2	28	70	40			38	41	12	9	+	—	—	—	+	—
			L	17	57	26	20			58	9	23	10	+	—	—	—	+	
VII	1.4	Sand		92	5	2	5	2.6	0.56					+	—	—		—	
VI	1.0	Mudstone		16	42	42	46			63	11	19	8	+		—	—	+	—
V	3.0	Mudstone	U	32	34	34	19			55	13	20	12	+	—		—	+	—
			L	1	41	58	31			51	23	18	7	+	—			+	
IV	0.5	Sand		100	0	0	0	2.5	0.73					+	—	—		—	
		Silty chips		0	62	38	3			68	0	22	10	+			—	+	
III	3.7	Mudstone	U	2	34	64	35			50	21	24	5	+	—	—	—	+	—
			L	24	34	42	23			68	0	28	4	+	—	—	—	+	
II	7.6	Sand	U	97	3	0	3	3.2	0.82					+	—	—		—	
I	0.4	Mudstone		1	33	66	36			44	33	10	13	+	—	—	—	+	—
—	0.8+	Tsondab Ss		97	2	1	4	2.5	0.30					+	—	—		—	
Linear dunes of region				100	0	0	—	1.8—2.75	0.20—0.90					+	+	—			

[a]U = Upper; L = Lower. [b]Determined by first removing carbonates in HCl, then removal of sand by wet sieving, followed by hydrometer analysis for silt and clay. [c]In phi units, using Folk and Ward (1957) graphic calculations. [d]I = illite; Ex = expandables; K = kaolinite; C = chlorite. Determined by measurement of peak heights of X-ray diffractograms; clay slides glycolated and heated to 340°C and 500°C (I = 10 Å peak glycolated; Ex = 10 Å peak heated to 340°C —10 Å peak glycolated; K + C = 7 Å peak; C = 7 Å peak heated to 500°C). [e]Qtz = quartz, Alb = albite, Dar = dark and opaque grains, Mic = mica, Cal = calcite, Hal = halite; + = major component, — = minor component (<10%).

grains in the sequence are lightly iron stained. Typically this stain is uniform and transparent, imparting a light to dark "amber" colour (close to reddish yellow, 7.5 YR 7/6). Some grains have a distinct "red" appearance, with red (e.g. 2.5 YR 4/8, 10 R 4/8) in pits and embayments and a lighter pale red to amber colour outside of those embayments. The overall colour of the sand units changes upward in the section, from stronger reds of the Tsondab Sandstone (overall yellowish red, 5 YR 5/8) to mainly pale pink or amber colours (reddish yellow, 7.5 YR 6/6, 5 YR 6/6; pink, 7.5 YR 7/4) in the upper sands. Units immediately above the Tsondab Sandstone, and units IX and X, contain more of the irregularly-stained red grains than do other units.

Mudstone units

In the calcareous mudstones (Figs.3 and 4), calcite makes up from 19 to 46% of the total rock, with an average of more than 30% (Table I). Of the insoluble residue in these mudstones, sand typically makes up less than 10% of the total, although there is considerable variability at a fine scale. In units III and VIII the sand content declines toward the top of the unit, whereas in unit V it increases from less than 1% near the base to more than 30% in the upper 30 cm. As the sand content rises, the clay content declines, while the silt percentage remains relatively constant between 32 and 42%. Most calcareous mudstones are laminated where sandy and massive to poorly laminated elsewhere. Vertical mudcracks or a polygonal network of fractures, filled with halite and/or a fine sand or silt, are common in those parts of mudstone units I, III, VI, and X that contain little sand.

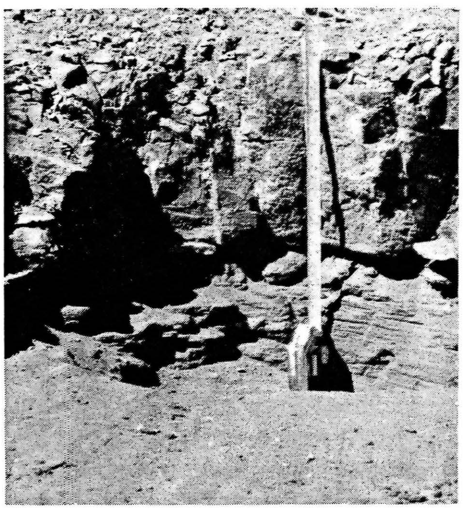

Fig.3. Base of calcareous mudstone of Unit I overlying laminated Tertiary Tsondab Sandstone Formation.

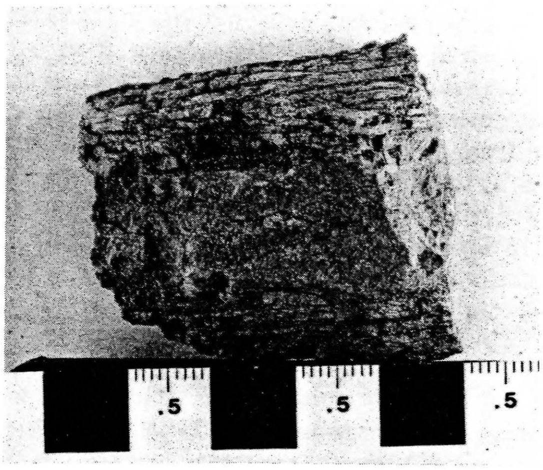

Fig.4. Laminated calcareous mudstone of unit VI; scale in centimeters.

Mineralogically, the sand in the mudstones is similar to that in the interbedded sand units, being comprised mainly of quartz, with minor amounts of albite and dark minerals (Table I). In contrast to the sand units, mica is present in most of the mudstones. The suite of clay minerals is dominated by illite (which probably includes fine-grained muscovite). Kaolinite makes up a relatively constant 10—30% and chlorite comprises the smallest percentage of the clay mineral suite, averaging less than 15% in all units. The expandable clay content (smectite) varies considerably, with the highest percentages in the most clayey zones (Table I). The characteristics of the sand-sized quartz grains in the mudstones are similar to those of the interbedded sand units. Nearly all are subrounded to rounded. The "amber" and "red" stain on the silt and sand grains combines with the very pale brown (10 YR 8/3) to white (10 YR 8/2) colour of the finer components in the mudstone to give a pinkish grey (7.5 YR 7/3) to pinkish white (7.5 YR 8/2) colour where these grains are in great enough abundance.

Diatoms

Only four samples, from units, I, III, IV, and VIII, were examined for diatoms. Dr. Gordon Goldsborough (Botany Department, University of Manitoba) found diatoms only in unit IV, which is a fine sand containing calcareous clayey silt laminae. Of the eight species identified (Table II) *Tabellaria fenestrata* was the most abundant. All diatoms are planktonic and freshwater species, characteristic of high nutrient (eutrophic) lakes.

TABLE II

Diatoms identified from unit IV by G. Goldborough

Tabellaria fenestrata
Navicula sp. (possibly *N. pseudolancedata*)
Cyclotella kutzingiana
Synedra delicatissima var. *angustissima*
Asterionella formosa
Nitzschia palea
Melosira italica
Fragilaria vaucheriae var. *vaucheriae*

RADIOMETRIC DATES AND ARTIFACTS

Three of the calcareous mudstone units at Narabeb have been radiocarbon dated. Table III gives these and other dates, along with other relevant information.

We believe that four of the radiocarbon dates, 22,500, 20,320, 22,330, and 26,400 yr B.P., may represent the approximate true age of deposition of the post-Tsondab Sandstone sequence at Narabeb. The dated pedotubules below this sequence, in the upper part of the Tsondab Formation, may reflect a slightly earlier wet phase, whereas the old basal date in the sequence may be due to incorporation of older carbonate. Although it is possible that post-depositional remobilization of the calcite has occurred and, therefore, that the sequence is older than these dates, microscopic examination of the dated mudstones does not indicate that the calcite has been recrystallized. Furthermore, the close association of carbonate with specific horizontal stratigraphic units, and its near absence in permeable units immediately above and below them, indicates that little, if any, post-depositional movement of calcite has occurred. Further support for accepting the 20,000—26,000 yr B.P. radiocarbon dates as representing the time of deposition — and for rejecting recrystallization of the calcite — is the fact that the $^{13}C/^{12}C$ ratios in units V and X are strongly positive (+6.56‰ and +6.40‰, respectively). While these values do not rule out the possibility of any post-depositional isotopic change, complete recrystallization of the dated carbonate and resetting of its ^{14}C age seems unlikely (T. Cerling, pers. commun., 1985).

On the other hand, the great age for the lower unit, based on $^{234}U/^{230}Th$ dating (Selby et al., 1979), may be suspect. Unlike sediments comprised entirely of authigenic minerals such as calcite, calcareous mudstones that contain ancient clay particles may contain uranium/thorium ratios that reflect the age of the bedrock from which the detrital clays were derived, rather than the radiometric age of the penecontemporaneously deposited carbonate (cf. Schwarcz, 1978).

Hundreds of stone implements, including handaxes, choppers, cleavers, flakes, and cores, have been found in the Narabeb area by Seely and

TABLE III

Radiometric dates from the sediments at Narabeb

Unit in sequence shown in Fig.2	Age in yrs B.P.	Lab No.	Method[a] and sediment	Source
X, lower half	22,330 ± 600	Beta — 9116	^{14}C, calcareous mudstone	new
X?	26,400 ± 340	Pta — 3759	^{14}C, calcareous silt	new, J. Vogel (unpublished)
V, basal 30 cm	20,320 ± 300	Beta — 9115	^{14}C, calcareous mudstone	new
I, top 1 cm	22,500 ± 280	Pta — 3704	^{14}C, calcareous mudstone	new, J. Vogel (unpublished)
I, basal 20 cm	39,800 ± 1700	Pta — 3770	^{14}C, calcareous mudstone	new, J. Vogel (unpublished)
pedotubles in Tsondab Ss	28,500 ± 500	Pta — 1197	^{14}C, calcite in sandstone	Vogel and Viser (1981)
I?	210,000 ± 15,000	—	$^{234}U/^{230}Th$, calcareous mudstone	Selby et al. (1979)
I?	260,000 ± 25,000	—	$^{234}U/^{230}Th$, calcareous mudstone	Selby et al. (1979)

[a]Carbonate ages adjusted for $^{13}C/^{12}C$.

Sandelowsky (1974). They report that the greatest concentration in this region is within a radius of about 2 km of the ancient calcareous sediments described in this paper. All artifacts were found lying on the modern surface and display a desert varnish. The absence of size sorting and abrasion "suggest that they are in primary context". (Seely and Sandelowsky, 1974, p. 63) These artifacts were interpreted as Early Stone Age implements by Seely and Sandelowsky (1974). Shackley (1985) notes that both Early and Middle Stone Age artifacts occur at Narabeb and in its immediate vicinity. Middle Stone Age materials are known from many other areas in the Namib Desert (Korn and Martin, 1957), which are today hyper-arid. The occurrence of both Early and Middle Stone Age artifacts in the area suggests a long history of periods of increased moisture availability in the vicinity of Narabeb.

RELATION TO OTHER SEDIMENTS

Correlation of late Cenozoic clays, silts, sands, and carbonates in the Namib Desert is difficult. Both the paucity of reliable dates and the widely scattered nature of these deposits contribute to this difficulty. Thick pedogenic calcretes in the central Namib Desert, which formed after deposition of the Tertiary sequence (Yaalon and Ward, 1982), should not be confused with primary limestone deposited from evaporating surface waters like that at Narabeb.

There is no known sequence of calcareous mudstone in the Namib that compares in thickness to that at Narabeb. There are, however, a number of localities in interdune depressions in the northern part of the Namib Sand Sea where thin calcareous mudstones are exposed at the surface. As at Narabeb, their known areal extent is small, being limited by active linear dunes. "Fossil reeds, or their leaf imprints, occur often in association with pan/lacustrine carbonates, e.g. Khommabes, near Gobabeb, Meob and Conception Bays [Vogel and Viser, 1981; Teller and Lancaster, 1985], and Koichab Pan, or with calc-tufa spring deposits, e.g. Hudaob (Kuiseb River)." (Ward et al., 1983, p. 180). The radiocarbon ages of these deposits and of others at Homeb, Tsondab Vlei, Sossus Vlei, and Koichab Pan (Figs.1 and 5) (Vogel and Viser, 1981) fall into two groups: 10,000—14,000 yr B.P. (Meob, Homeb, Tsondab Vlei, Sossus Vlei, and Conception Bay) and 20,000—35,000 yr B.P. (Narabeb, Homeb, Khommabes, and Koichab Pan). Interestingly, many other dated carbonates in the Namib, including shells, "calcified" silt, and calcrete near Homeb and Tsondab (Vogel and Viser, 1981), as well as pedogenic calcretes elsewhere, also fall into these two age groups.

Most of the silt- and sand-sized grains in the calcareous mudstones at Narabeb bear a strong resemblance to those of the interbedded sands, as well as to aeolian sands described throughout the Namib. The normal presence of mica in this coarser fraction, however, is distinctive (Table I). Some of the fine-grained fluvial sediments of Tsondab Vlei, 38 km to the east, and of its northwestward extension (Marker, 1979; Lancaster, N., 1984) resemble the

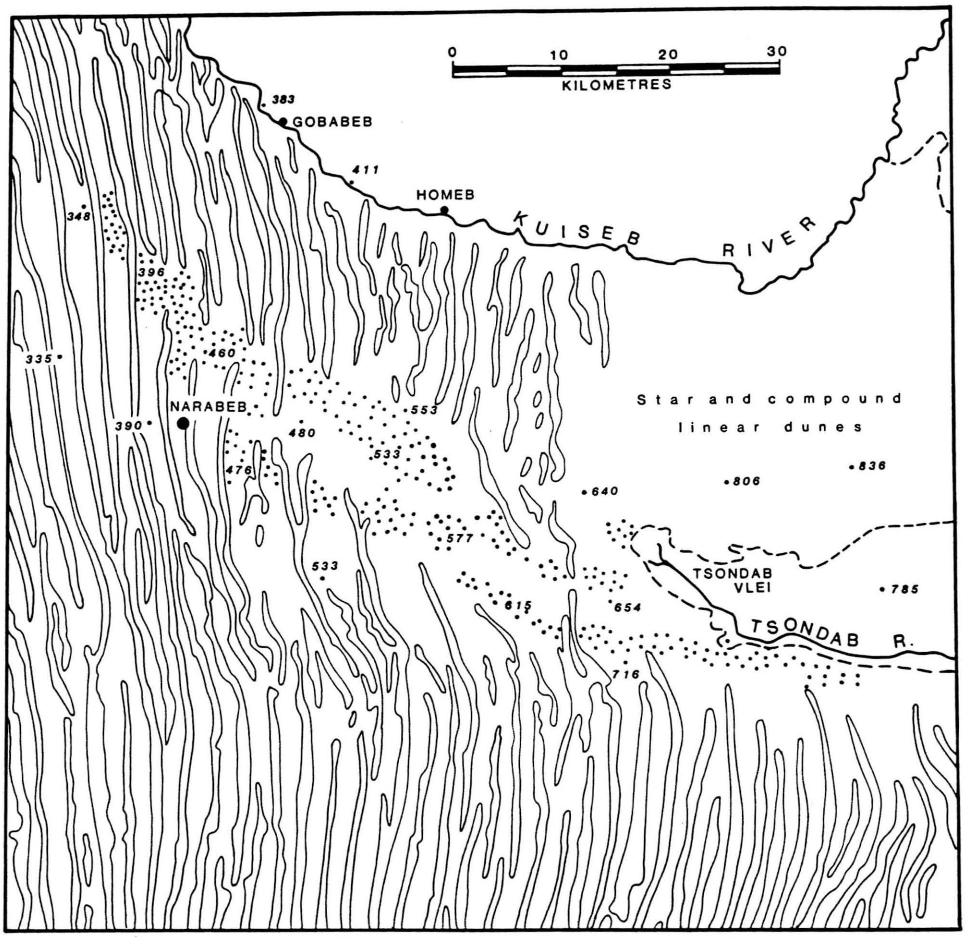

Fig.5. Narabeb and its relation to fluvial silts, sands, and gravels (stippled pattern) west of Tsondab Vlei (after Lancaster, 1984) and to linear dunes in the Sand Sea. Northern margin of Sand Sea is at Kuiseb River; eastern extent shown by dashed line. Spot elevations (in meters) and dune outline from 1:250,000 topographic maps.

mudstones at Narabeb, but radiocarbon dates from there are distinctly younger (13,000—14,000 yr B.P., Vogel and Viser, 1981).

The sand that is interbedded with the calcareous mudstones at Narabeb is similar in most of its characteristics to modern aeolian sands, which bear many of the properties of the Tertiary Tsondab Sandstone Formation described in this paper and by Besler and Marker (1979). The likelihood that most sand-sized sediment in the arid Namib Sand Sea has had a common heritage accounts for this similarity.

INTERPRETATION

Sedimentology at Narabeb

Mudstones

The alternating sequence of calcareous mudstones and sands exposed in the interdune corridor at Narabeb reflects a fluctuation in available water. The dominance of clay- and silt-sized particles in the mudstones, cemented by calcite, indicates that they were deposited in a relatively quiet-water environment, where the fines could settle out of suspension while carbonate was being precipitated. The restriction of the high carbonate content to the silt and clay units, and the fact that these units are bounded by horizontal bedding planes, indicate that the calcite is not a secondary precipitate such as calcrete.

Although it is possible that groundwater seepage may have provided some water to this site, the abundance of mica and the high percentage of clays and silts in the mudstones, seem to demand a surface flow of water to Narabeb from outside of the main Sand Sea. This necessitates a dune-free avenue upslope (eastward) from Narabeb, which would have allowed runoff across the seaward-sloping bedrock surface, probably from the Great Escarpment. The red- and amber-stained coarse silt and sand fraction, and the overall mineralogy of the mudstones, indicates that the Tsondab Sandstone and/or younger aeolian deposits were the probable source for some of the sediment. The presence of horizontal laminae (e.g. Fig.4) in the sandy mudstones, and absence of other sedimentary structures such as ripples and cross-bedding, further support the view that the mudstones were deposited in a quiet-water environment such as a small lake, into which sandy sediment was periodically washed or blown. The presence of possible mudcracks, infilled by halite, sand, and/or silt, (units I, III, VI, and X) is related to drying that followed deposition of the calcareous muds.

The diatoms identified in Unit IV (Table II) are freshwater types, characteristic of nutrient-rich (eutrophic) waters (G. Goldsborough, pers. commun., 1984). Richardson et al. (1978) indicate that these types typically are found in medium to low alkalinity shallow lakes of East Africa.

Although there is no other direct evidence of organic productivity in the Narabeb basin, the high $^{13}C/^{12}C$ values in the carbonate of units V and X may be the result of fermentation of organic matter (i.e. methanogenesis) in the mud (T. Cerling, pers. commun., 1985). In this process, the degradation of organic matter results in fractionation into methane, which is isotopically light, and carbon dioxide, which is heavy:

$$2CH_2O = CH_4 + CO_2$$

The formation of carbonate from this CO_2 results in a high $^{13}C/^{12}C$ ratio (Irwin et al., 1977).

Sands

The fine to very fine, moderately well sorted sands that are interbedded with the mudstones also display a horizontally laminated structure; no cross bedding or cut and fill structures were observed, and only Unit II contains granule or very coarse sand grains. The quartz grains are mainly subrounded, and are variably stained an amber to red colour — very similar to grains in the modern linear dunes of the Namib. Although an aeolian origin for the interbedded sand at Narabeb can be postulated on the basis of degree of sorting and similarity to modern aeolian sediment, reworking of aeolian materials by running water is also possible. The widespread Tertiary-age Tsondab Sandstone, which underlies much of the region, is also similar to the sands at Narabeb. The absence of mica in these sands supports the idea that they either were deposited by the wind or, if water deposited, were derived from sediment that was originally deposited by the wind.

The presence of fragmented clayey silt laminae within some sand units, (units II, IV, IX) also provides information about the origin of the sand. We suggest that these fragments were formed in one of the following ways: (1) Deflation and redeposition of the cohesive chips from nearby water-laid deposits, which had been fragmented by the growth of efflorescent salts, shrinkage during drying, or disturbance by animals. (2) Deposition in relatively quiet water at the present site during a brief period of ponding or high water, with later disturbance by animals (bioturbation) or fragmentation by desiccation.

The low, but persistent occurrence of carbonate in all but the upper sand unit (where only the basal and scattered upper zones are calcareous) may indicate that deposition was in (or by) carbonate-bearing water. Alternatively, this carbonate may have been introduced by dust deflated from nearby carbonate-rich sediment. We favour the idea that the carbonate was precipitated within water-saturated sand at the time that the overlying unit of calcareous mud was deposited. This would explain the absence of calcite in most of the uppermost sand (unit XI), where no later ponding appears to have occurred. We also recognize that groundwater may have introduced or remobilized local carbonate after the entire sequence was deposited.

Considering the above, we propose that the sand units in the sequence at Narabeb were deposited mainly by wind, during intervals when water was not standing in this depression. The source for these sands may have been nearby dunes, fluvial deposits, and/or the Tsondab Sandstone Formation. The dominantly horizontal laminae suggest that the sands were not part of a dune complex migrating across the depression. The clayey silt chips in several of the units are similar to those found in the sand of present-day active dunes close to the deflating Narabeb mudstones, and, therefore, seem to represent ancient episodes of deflation from previously deposited muds, perhaps from the immediately underlying unit.

The preservation of the sands is the result of partial cementation by calcite and of the resistant calcareous mudstones that cap most of these units. Even the mudstones, however, are physically decomposing today, and preserved remnants of this sequence at Narabeb must be attributed to protective burial by dunes in the modern Sand Sea.

History of sedimentation at Narabeb

The extreme aridity of the Namib precludes the ponding of water from local rainfall and runoff at Narabeb today. In addition, the topographic isolation of most depressions in the Sand Sea, caused by large and extensive linear and transverse dunes, prevents the influx of water from wetter regions that lie upslope to the east. In order to explain the history of deposition at Narabeb, we must consider the possibility that one or both of these conditions — hyper-aridity and isolation — may not have existed in the past.

Variations in late Quaternary rainfall in arid regions of Africa and Australia have been discussed by many (e.g. Bowler et al., 1976; Van Zinderen Bakker, 1976; Rognon and Williams, 1977; Bowler, 1978; Street and Grove, 1979). The evidence for southern Africa has been recently summarized by Heine (1982) and Deacon et al. (1984). The best documented precipitation increases occurred just prior to and during the main phase of glaciation in the Northern Hemisphere, about 40,000—20,000 yr B.P., and near the end of glaciation, 14,000—7000 yr B.P.

Such increases in rainfall probably would have influenced the flow of rivers in the Namib, most of which received the largest part of their runoff from their headwaters in the Great Escarpment (Fig.1). The actual time of increase in river flow has not been established in the region, although at Narabeb and elsewhere a clustering of radiocarbon dates in the 20,000—35,000 yr B.P. period indicates that conditions were (at least periodically) wetter during that period of time. This is in agreement with the "pluvial conditions" that existed between about 19,000 and 30,000 yr B.P. to the east in the Kalahari (Heine, 1982) and elsewhere (e.g. Street and Grove, 1979). The widespread occurrence of Middle Stone Age material in the driest parts of the Namib Desert, and the apparent restriction of Late Stone Age material to "favourable" sites, such as waterholes and springs (Korn and Martin, 1957), indicate that conditions were wetter in this region prior to the last glacial maximum than at any time since then. After about 20,000 yr B.P., only a brief period between about 10,000—14,000 yr B.P. experienced conditions significantly wetter than those of today.

Although an increase in rainfall in the eastern part of the region would have influenced the rivers that crossed the Namib to the Atlantic Ocean, as well as those that terminate in the eastern Namib Sand Sea (cf. Van Zinderen Bakker, 1976; Ward et al., 1983), it is unlikely that the aridity of the Namib was substantially diminished for any length of time during the Quaternary. In fact, nearly all studies, including those of the rich endemic life forms, strongly suggest that "the current desert regime of the Namib dates from the Late Tertiary, with the Quaternary climatic . . . fluctuations superimposed on a dominant, and possibly progressive, aridifying trend." (Ward et al., 1983, p. 181). The presence of the cold Benguela Current since Miocene time has assured the continuing aridity of coastal Namibia and of the region inland for many kilometers.

For this reason, the occurrence of freshwater lacustrine sediments at Narabeb, deep within the central part of the Sand Sea and only 47 km from the Atlantic coast, requires further explanation. Seely and Sandelowsky (1974) proposed that Narabeb was at one time the end point of the Tsondab River (Fig.1). Besler and Marker (1979), Marker (1979), Besler (1980), and Lancaster, N. (1984) present data to support the former westward extension of the Tsondab River into the present Sand Sea. Although no other calcareous mudstones comparable in thickness to those at Narabeb are known from this ancient water course, fluvial deposits of silt, sand, and gravel are exposed at intervals along the now-abandoned route, where not buried by dunes (Fig.5). Both Seely and Sandelowsky (1974) and Wienecke and Rust (1972) suggest that the Tsondab River has not flowed west as far as the Atlantic since middle Quaternary time.

We feel that the deposits at Narabeb represent a former end point of the Tsondab River, established as encroaching dunes prevented the westward flow of runoff to the Atlantic. The present isolation of this site came about as linear dunes gradually invaded the bed of the Tsondab River to the east of Narabeb. The distribution of fluvial sediments to the northwest of Tsondab Vlei (Fig.5) indicates that the course of the Tsondab River shifted northward from Narabeb as the Sand Sea migrated toward the north (cf. Besler, 1980, map 7). The absence of distinct linear dunes in much of the area where fluvial sediments are found (Fig.5), and their presence to the north, suggests that the Tsondab River continued to flow west toward Narabeb even after the Sand Sea had advanced to the Kuiseb River. Based upon freshwater molluscs and calcareous silt at a site 6 km west of Tsondab Vlei (Seeley and Sandelowsky, 1974), which are radiocarbon dated at 13,300—14,300 yr B.P. (Vogel and Viser, 1981) and are now separated from the Vlei by several 100-m high dunes, the terminus of the Tsondab River must have retreated from Narabeb before 14,000 yr B.P. and to its present position after 13,000 yr B.P.

Conclusions

The unique 36-m section of calcareous mudstones and sand at Narabeb represents an alternation of wet and dry events in the Namib. The mudstones were deposited in a lake. Although some of the coarser fraction in the mudstones probably was derived locally from aeolian sediments of the Namib Sand Sea or from the Tertiary Tsondab Sandstone Formation, most of the silt and clay had an origin many kilometers to the east. Both the carbonate and the coarse and fine components were deposited at the former terminus of the Tsondab River channel in a depression dammed by linear dunes of the

Sand Sea. The northern margin of the Sand Sea to the east of Narabeb may have been temporarily controlled during this time by periodic flows, which scoured the influx of aeolian sand and prevented linear dunes from crossing the channel to the north. Eventually, probably in response to a decline in rainfall, linear dunes crossed the Tsondab channel and dammed the system eastward to Tsondab Vlei, 38 km to the east, isolating the former end point of the river at Narabeb from further runoff. It seems likely that the Tsondab River was at first progressively displaced toward the north after the route to Narabeb was closed, and fluvial deposits to the north mark this now-abandoned river course (Fig.5). The present end point of the river at Tsondab Vlei was established after 13,000 yr B.P.

The six calcareous mudstones at Narabeb represent at least six long episodes of ponding, during which time Tsondab River runoff was concentrated enough to allow precipitation of calcite along with the clastic muds. The variability in coarse-grained material within the mudstones probably reflects a variation in river discharge reaching the site or in aeolian influx to the lake. The thick sands that lie between each mudstone probably represent aeolian deposition during intervening dry phases in the Narabeb depression, although it is possible that the course of runoff and the locus of deposition may simply have shifted away from Narabeb during these times. Infilled mudcracks in some of the mudstones attest to desiccation phases, as does the presence of calcareous mud chips in the sand units, which were derived from the dry lake bed.

The age of the deposits at Narabeb remains uncertain. Radiocarbon dates on the calcareous mudstones here, as well as on carbonates elsewhere in the Namib, indicate that the period between 20,000 and 35,000 yr B.P. was wetter than at present. Although we propose that lacustrine deposition at Narabeb took place episodically at the former terminus of the Tsondab River during this period, there is conflicting chronological data. First, if the Early or Middle Stone Age artifacts were associated with people that came to Narabeb because of the wetter conditions, then the age of the lacustrine deposits must be greater than about 25,000 yr B.P. Second, if the $^{234}U/^{230}Th$ dates of more than 200,000 yr B.P. are accepted, lacustrine deposition cannot be related to the last global cooling. If we accept the pre-late Quaternary age for the Narabeb deposits, then their radiocarbon age, and perhaps that of similarly dated carbonates in the region, must be attributed to recrystallization of calcite during the 20,000—35,000 yr B.P. period.

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