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The Tsondab Sandstone in Namibia and its significance for the Namib Erg

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Below the modern Namib sand sea in Namibia — one of the largest active ergs in the world — the Tertiary palaeo-erg of the Namib is preserved in the Tsondab Sandstone Formation. Outcrops and samples were subjected to structural and sedimentological analysis. Weak diagenesis and little cementation in many parts allowed the reconstruction of the Tertiary dune topography and prevailing wind regime during the last stage before planation. Tertiary sand sources seem to have been littoral sands in the coastal part and fluvial deposits along the rivers from the Great Escarpment. Dune sand consolidation occurred by clay infiltration, the growth of zeolites, and carbonate cementation. Large parts of the Miocene planation surface, which is uncovered in dune hollows and interdraa valleys, are preserved without much subsequent geomorphic modification. A detailed comparison of all sand properties and their spatial variations in the Tsondab Sandstone and in the Quaternary erg provides evidence that the Tertiary Tsondab Sandstone has been an important source of sands for the modern Namib Sand Sea.

Onder die moderne sandsee van die Namib — een van die groter aktiewe duinewoestyne in die wêreld — is die Tersiêre paleoduinewoestyn van die Namib gepreserveer in die Tsondab Sandsteen Formasie van Namibië. Dagsome en monsters is onderwerp aan strukturele en sedimentologiese analises. Swak diagenese en min sementering in baie dele maak herkonstruksie van die Tersiêre duintopografie en heersende winde gedurende die laaste stadium voor vlaktevorming moontlik. Tersiêre sandbronne blyk littorale sand in die kusgedeelte en fluviale afsettings langs die riviere van die Groot Eskarp te wees. Duinsandkonsolidering het plaasgevind deur infiltrasie van klei, die groei van seoliete, en deur karbonaatsementasie. Groot dele van die Mioseense planeringsoppervlak, wat blootgestel is in duinleegtes en interdraavalleie, is gepreserveer sonder veel daaropvolgende geomorfiese wysigings. 'n Gedetailleerde vergelyking van alle sandeienskappe en hul ruimtelike variasies in die Tsondab Sandsteen en in die Kwartêre duinewoestyn verskaf bewyse dat die Tersiêre Tsondab Sandsteen 'n belangrike bron van sande vir die moderne Sandsee van die Namib was.

Introduction: The Namib Erg and the Tsondab Sandstone

The Namib sand sea, one of the largest active ergs in the world, is situated on the west coast of Namibia (South West Africa) and covers 34 000 km^2. As can be seen on the Gemini V satellite image of the central Namib, the topography is modelled by transverse dunes in the coastal part, longitudinal megadunes or draa in the middle part, and very complex patterns in the east (Besler, 1980). Almost everywhere active dunes are superimposed on the stable draa. An early Skylab photo covers just about the total erg from the Kuiseb River near Walvis Bay in the north to the Koichab River near Lüderitz in the south, and to the Great Escarpment in the east (Besler, 1975). Colour differences on this image indicate outcrops of consolidated material or older surfaces in interdraa valleys in the north and in larger parts in the south.

Field work in 1976 revealed that the total Namib Erg is situated on a consolidated palaeo-erg (Besler, 1976/77; 1980; 1984; Besler & Marker, 1979). Aeolian sandstone was found in dune hollows even where interdraa valleys are filled with sand. The first author who mentioned sandstone below the dunefield was Stapff in 1887. Martin (1950) called it a Tertiary dune complex. SACS (1980) allocated Formation status to this unit, the type locality being Tsondab Vley. A detailed stratigraphic record was presented by Ward (1984) in his thesis on the Cenozoic geology in the Kuiseb Valley. According to Ward (1987; 1988a) the Tsondab Sandstone can be divided into six principal facies: a basal breccia (A), a colluvial conglomerate (B), a consolidated reddish aeolian quartz arenite (C), a massive reddish quartz arenite cemented by carbonate and gypsum (D), a mottled quartz arenite (E), and a carbonate member (F). Below the modern erg, facies C is found mainly in the western and southern parts and facies D mainly in the northeastern part (Besler & Marker, 1979; Besler, 1980).

The sandstone was sampled wherever it was found (Figure 1), and bedding structures were measured. It was found that generally, the steeper dips of slip faces pointed between north and east, which are also the resultant directions in the modern erg (details in Besler & Pfeiffer, 1993).

Tsondab Sandstone

Surface features

The main gradients of the sandstone surface below the erg were reconstructed from ground control and topographic profiles (Besler, 1980; 1984). The larger part — especially in the south — is sloping at 1% towards the ocean. This is the gradient of the Namib Plain outside the erg. Thus, the 'Post African Land Surface' (discussion in Besler, 1991) is also present below the sand sea.

Only west of the Naukluft Mountains is the surface less inclined, which is shown especially by the 250 m contour line on topographic maps (Figure 1). Here the surface is bevelled by fluvial erosion, and limestone and dolomite pebbles thin out towards the west. In the eastern part conditions were favourable for the development of calcretes which correspond to the main calcrete surface found in many places in Namibia (Blümel, 1981: 'Hauptkrustenfläche'; Besler *et al.*, 1994). This is Ward's Kamberg Calcrete which also developed in the Karpfenkliff Conglomerate (Ward, 1984; 1987). As Ward assigned a Miocene age to these conglomerates based on correlation and stratigraphy, then the partly calcrete-covered planation surface below the (northern) erg should also be of Miocene age. But whereas the Kamberg Calcrete in the type locality and in the eastern part of the Tsondab Sandstone is of

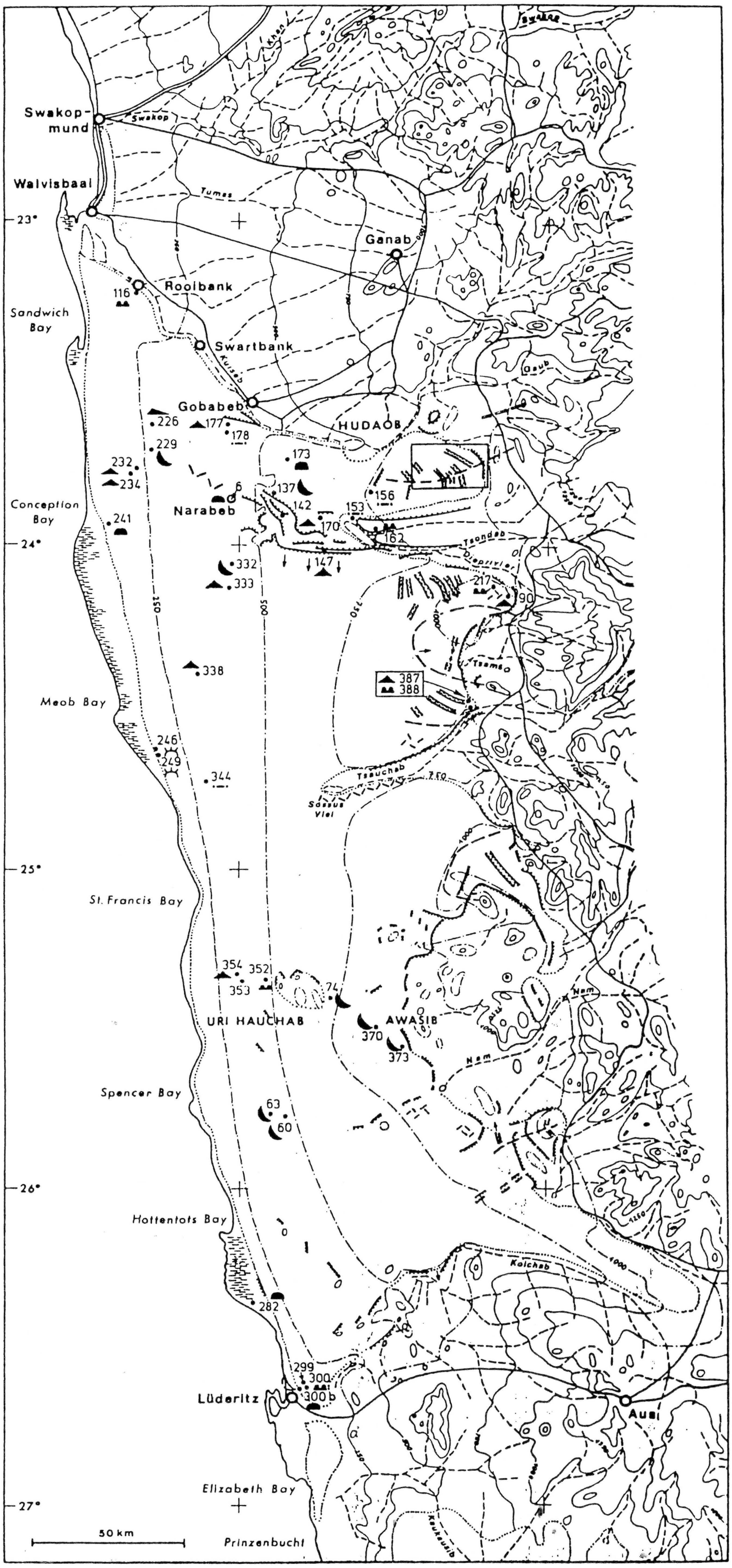

Figure 1 Sandstone modelling of the land surface below the Namib Erg (from Besler, 1980) and distribution of granulometric sand types in the near-surface Tsondab Sandstone. 1: active dune crest, 2: old barchan dune, 3: fluvial deposit, 4: inactive crest or flank of dune, 5: deflated dune, 6: nebkha, 8: young dune.

pedogenic origin, this is not necessarily the case for the calcretes in the interior erg as the carbonate pebbles corresponding to the quartzose Karpfenkliff Conglomerate promoted a synsedimentary calcrete formation (Wenzenz, 1975). This is corroborated by the fact that calcretes are found only on surfaces covered with carbonate pebbles (Besler, 1980, map 5).

According to Pickford (pers. comm., 1994), the calcretes of the Tsauchab–Elim–Tsondab region formed during the upper Pleistocene because they contain Middle Stone Age tools and a modern fauna. In spite of this, the surface could be of the same Miocene age as Blümel's main calcrete surface (Hauptkrustenfläche) as a topographic feature, or Ward's Camberg Calcrete as a geological formation. In his thesis on calcrete generations in Namibia, Eitel (1993; 1994) has shown that the remobilization of carbonates and their aeolian distribution lead, not only to the formation of younger calcretes on other surfaces, but also to the widespread development of polygenetic calcretes on the Miocene main calcrete surface. There is agreement that detailed mapping and analysis of the calcretes is necessary.

Apart from the bordering rivers, Kuiseb and Koichab, at least four ancient river systems have modelled the sandstone

Table 1 Analytical properties of sampled sandstones (for sampling sites see Figure 1)

No.	Salinity	Friability	Mz (mm)	So (Φ)	Colour	$CaCO_3$(%)	Zeolites	Patina (%)	Grain Type
6	–	medium	0.2216	0.8347	5 YR 4/6	0	+	89	subang.–frost.
60	–	medium	0.2705	0.8947	5 YR 4/6	0.79	+	49	rounded–frost.
63	–	high	0.2105	0.9163	7,5 YR 5/6	0.95	+	71	subang.–frost.
74	–	high	0.3396	0.5249	10 YR 5/3	0	–	0	subang.–clear
90	–	medium	0.1172	0.9503	5 YR 5/4	0	–	97	subang.–frost.
116	strong	low	0.0727	11.2439	5 YR 6/4		–		subang.–clear.
137	–	high	0.2446	0.4560	7,5 YR 6/4	5.07	–	16	mixed
142	–	high	0.1746	1.1565	5 YR 4/6	0	+	93	subang.–frost.
147	–	–	0.1101	0.8485	5 YR 4/6	8.61	+		rounded–frost.
153	medium	high	0.1437	1.1309	2.5 YR 5/4	2.73	+	92	subang.–frost.
156	–	medium	0.1727	1.0233	2.5 YR 4/4	4.12	+	95	subang.–frost.
162	strong	low	0.0813	1.2615	2.5 YR 5/4	2.35	+	96	subang.–frost.
170	strong	low	0.2312	0.8264	7.5 YR 5/4	1.99	–	86	subang.–frost.
173	medium	medium	0.1038	1.3704	5 YR 5/4	19.98	–	100	subang.–frost.
177	medium	medium	0.1261	0.9908	7.5 YR 5/4	8.29	+	88	subang.–frost.
178	strong	high	0.1936	0.9193	5 YR 4/6	3.89	–	94	subang.–frost.
217	medium	low	0.0811	1.1230	5 YR 5/4	1.44	–	97	subang.–frost.
226	strong	low	0.1047	1.2165	5 YR 5/4	5.95	–	9	mixed
229	medium	high	0.2858	0.6689	10 YR 5/4	1.16	–	21	subang.–frost.
232	–	medium	0.1606	0.6164	5 YR 5/6	0	–	90	subang.–clear
234	medium	high	0.1617	0.6683	5 YR 5/6	0	–	52	subang.–clear
241	medium	low	0.2072	0.6836	10 YR 6/3	0	+	8	mixed
246	medium	low	0.2277	1.0452	5 YR 4/6	0.57	–	53	subang.–frost.
249	medium	high	0.1900	1.2547	10 YR 7/2	22.11	–	2	mixed
282	medium	high	0.2180	1.3303	10 YR 6/3	9.80	–	5	subang.–frost.
299	medium	low	0.3842	6.7065	10 YR 6/3	1.87	–	0	subang.–frost.
300	strong	low	0.1449	1.4792	10 YR 7/2		–	7	subang.–frost.
300b	–	low	0.2550	1.1682	5 YR 5/4	0	–	93	subang.–frost.
332	–	high	0.2005	0.7839	5 YR 5/4	0	+	90	subang.–frost.
333	medium	low	0.1365	1.0365	5 YR 5/4	1.86	+	91	subang.–frost.
338	–	low	0.1577	0.8288	5 YR 4/8	0	–	95	subang.–clear
344	–	high	0.2430	0.9645	7.5 YR 6/4	0.24	–	19	subang.–clear
352	–	low	0.1113	1.5587	5 YR 4/6	3.34	+	84	subang.–clear
353	–	high	0.2436	1.5689	5 YR 5/4	0.16	+	66	mixed
354	–	high	0.1558	0.7866	5 YR 5/4	0	+	29	mixed
370	–	high	0.1969	0.8486	10 YR 5/3	0.37	+	19	rounded–frost.
373	–	medium	0.2101	0.8882	10 YR 5/3	0	+	86	subang.–frost.
387	medium	medium	0.1373	0.9132	5 YR 4/4	1.97	+	98	subang.–frost.
388	medium	medium	0.0690	1.2210	5 YR 6/3	33.09	–	100	mixed

Table 2 Heavy-mineral assemblages of the Tsondab Sandstone

No.	HM	ZR	TO	RU	ST	GA	BP	HB	PX	RE
01	7.1	1.0	2.0	–	–	–	3.0	13.0	81.0	–
06	8.0	–	–	–	–	2.0	–	11.0	87.0	–
60	21.6	1.0	–	0.5	–	4.0	–	3.0	90.5	1.0
63	4.2	–	–	2.0	–	2.0	2.0	4.0	90.0	–
74	11.3	–	0.5	0.5	–	16.0	0.5	2.0	78.0	2.5
90	1.2	4.0	–	3.0	–	59.0	3.0	11.0	19.0	1.0
116	0.7	–	8.0	–	14.0	39.0	8.0	1.0	29.0	1.0
137	7.6	1.0	1.0	–	0.5	23.0	1.0	3.0	70.0	0.5
142	1.4	1.0	–	–	–	3.0	–	6.0	90.0	–
147	0.4	5.0	–	1.0	–	5.0	2.0	6.0	81.0	–
153	1.0	3.0	1.0	1.0	0.5	66.5	–	5.0	21.0	2.0
156	0.2	5.0	–	4.0	–	24.0	–	12.0	55.0	–
162	2.6	4.0	2.0	0.5	0.5	17.0	–	31.0	43.0	2.0
170	2.6	1.0	–	0.5	–	10.0	0.5	10.0	78.0	–
173	0.4	13.0	1.0	4.0	–	29.0	1.0	16.0	36.0	–
177	0.6	1.0	–	–	–	4.0	–	5.0	89.0	1.0
178	11.8	2.0	–	–	–	3.0	–	7.0	88.0	–
202*	24.4	4.0	1.0	–	1.0	7.0	1.0	36.0	50.0	–
207	1.0	2.5	1.5	2.0	4.0	61.0	4.0	–	25.0	–
217	2.0	8.0	1.0	2.0	1.0	49.0	–	12.0	24.5	2.5
226	1.3	1.0	–	–	7.0	77.0	6.0	1.0	8.0	–
229	23.7	3.0	1.0	–	–	10.0	–	3.0	82.0	1.0
232	3.7	1.0	3.0	1.0	0.5	5.0	–	3.0	86.5	–
234	4.9	–	1.0	0.5	0.5	2.0.	–	1.0	93.0	2.0
241	5.4	–	–	–	0.5	3.0	1.0	4.0	88.0	3.5
246	7.6	2.0	–	–	–	3.0.	–	5.0	90.0	–
249	2.9	1.0	1.0	1.0	1.0	5.0	5.0	5.0	81.0	–
271	1.2	6.0	–	–	–	69.0	2.0	–	23.0	–
272	0.2	24.0	2.0	2.0	–	37.0	2.0	2.0	31.0	–
282	7.5	3.0	–	–	–	3.5	–	12.5	81.0	–
299	4.2	1.0	–	–	–	1.0	–	3.0	95.0	–
300	1.0.	1.0	2.0	–	–	11.0	–	10.0	76.0	–
300b	38.2	7.0	0.5	1.5	–	6.0	–	9.0	76.0	–
332	0.4	1.0	1.0	–	1.0	12.0	–	4.0	81.0	–
333	7.8	–	–	–	–	13.0	–	7.0	80.0	–
338	10.4	2.0	–	–	–	5.0	–	5.0	88.0	–
344	16.4	–	–	–	0.5	4.0	0.5	2.0	93.0	–
352	19.0	–	–	–	–	2.0	–	5.0	93.0	–
353	10.0	1.5	1.0	0.5	1.0	9.0	1.0	3.0	83.0	–
354	12.5	–	1.0	–	2.0	12.0	–	4.0	81.0	–
370	8.2	–	0.5	0.5	0.5	9.0	–	2.0	86.5	1.0
373	18.2	–	–	–	1.0	2.0	–	1.0	96.0	–
387	3.8	1.0	–	1.0	–	10.0	–	3.0	85.0	–
388	0.2	5.0	2.0	–	–	46.0	5.0	25.0	15.0	2.0
389	2.3	–	6.0	–	–	–	6.0	37.5	50.5	–

HM = Total heavy-mineral content
* = Etjo Sandstone
ZR = Zircon
TO = Tourmaline
RU = Rutile
ST = Staurolite
GA = Garnet
EP = Epidote
HB = Hornblende
PX = Pyroxene
RE = Rest

surface and can be traced by terraces and channels below the draa and dunes. The Tsondab system in the less inclined northern surface is most conspicuous and can be traced almost to the coast. The channels of Tsauchab, Nam, and of a Koichab tributary end in the eastern half of the erg (Figure 1; Besler, 1980).

The main calcrete mentioned above is only found on the broad high terraces (or old land surface) of Kuiseb and Tsondab. Calcrete detritus or secondary calcretes cover parts of the lower terraces. No calcretes are exposed on the 1% inclined surface farther south. Here, in places, carbonates are concentrated in root cast and/or termitaria structures which have been excavated by aeolian deflation.

Sedimentological analysis

About forty sandstone samples from outcrops in interdraa valleys and dune hollows were subjected to sedimentological analysis. Although being far from sufficient for a detailed study on the Tsondab Sandstone below the erg, the first approach gave very interesting results. Besides grain size distribution, properties like salinity, friability, colour, grain coatings, quartz grain shapes and surface texture, matrix constituents, and heavy minerals were investigated. The results are briefly summarized in Tables 1 and 2 (from Besler & Pfeiffer, 1993).

Morphology of the palaeo-erg

According to bedding structures, salinity, and grain size distributions, the near-surface Tsondab Sandstone is mostly aeolian. Ward (1988a) compared the stratification in sandstone exposures to modern dune types and their beddings, and found a great similarity between the distribution of dune types in the ancient Tertiary erg and the modern Namib Sand Sea in their northern parts: barchanoid ridges or transverse dunes in the coastal belt and star dunes on the eastern edge. But the linear draa in the interior part, because of their varying and intricate internal structures, could not be recognized in the Tsondab Sandstone. The granulometric analysis also gives conclusions concerning dune types and, therefore, a reconstruction of the morphology of the Tertiary palaeo-erg before the — most probably — Miocene planation. This is possible because world-wide investigations have shown that in all deserts there seem to exist only about a dozen granulometric sand types which are characterized by typical grain size frequency distributions if standardized techniques are used in analysis, calculation, and drawing (Besler, 1996). Especially important in this connection is the presentation of weight per cent per mm fraction interval on the Y-axis in the frequency distributions (Walger, 1964), which makes the curves more sensitive to grain transport processes.

A part of this technique has been challenged by Livingstone (1987; 1989), Thomas (1986), and Vincent (1985; 1988). The criticism partly results from a misunderstanding (Thomas, 1986) and partly from evidence derived from the study of barchan dunes (Vincent, 1985; 1988), which are an exception. Livingstone (1987; 1989) did not criticize the granulometric sand types resulting from different grain size frequency distributions but the response diagram (as did Vincent, 1985) which is not essential for the procedure applied here. Both the challenge and new results confirming the tech-

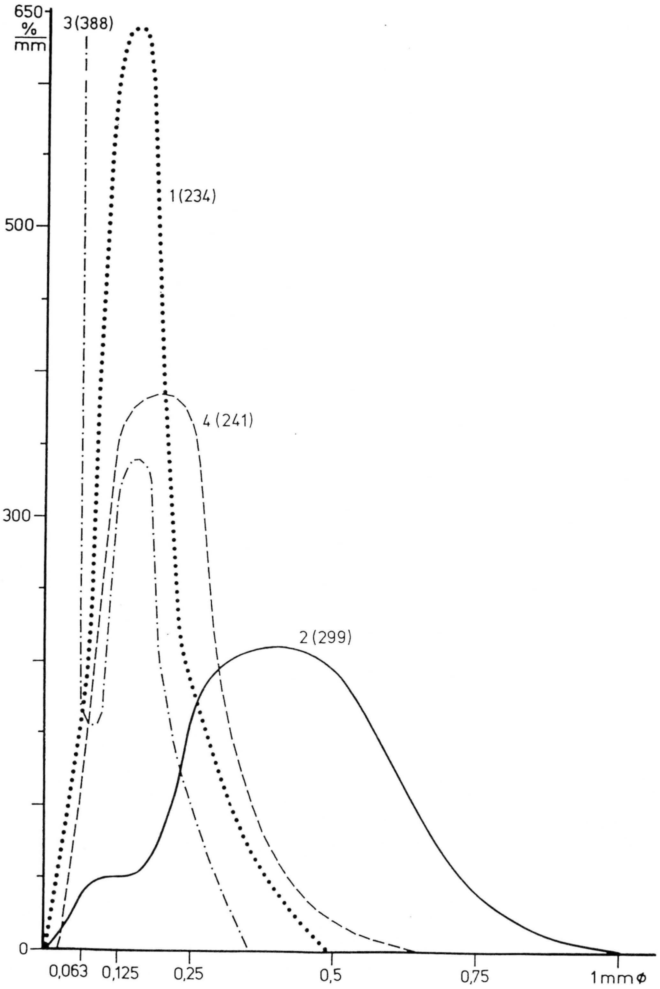

Figure 2 Frequency distributions of grain size in Tsondab Sandstones characteristic of sand types: 1: active dune crest, 2: barchan dune, 3: fluvial deposit, 4: inactive dune. Numbers in brackets give the sampling sites in Figure 1.

nique are discussed in Besler (1996). Additional techniques are necessary for sandstones. The diagenetic particles altering the original frequency distribution, forming larger aggregates, and/or mainly found in the fractions < 0.063 mm have to be quantitatively distinguished from original sand grains under a stereo-microcope and the calculations have to be corrected.

Seven granulometric sand types are present in the exposed Tsondab Sandstone (Figures 2 and 3). The frequency distribution no. 1 is characteristic of active dune crests of various dune types, including younger barchan dunes. The high and narrow peak in the interval 0.125 – 0.250 mm indicates good sorting and sand mobility.

Frequency distribution no. 2 is typical for older barchan dunes after a long period of migration. The broad maximum of 0.25 – 0.50 mm and the shoulder or small secondary maximum of 0.063 – 0.125 mm are the result of continued winnowing during migration. The final curve will be unimodal again.

Frequency distribution no. 3 stands for fluvial deposits in sandy deserts (no coarser material). Characteristic are the high clay and silt contents. The minimum of 0.063 – 0.125 mm indicates aeolian deflation.

Frequency distribution no. 4 is characteristic of inactive dune crests or flanks of (active) dunes. The subdued and broader peak — compared to active crests — indicates less sorting and reduced mobility. The threshold between types no. 1 and no. 4 seems to be around 400 per cent/mm.

The bimodal frequency distribution no. 5 (Figure 3) is typical for deflated dunes or dune plinths. The generally coarse sand is deprived of the aeolian main fraction of 0.125 – 0.250 mm. Smaller grains are protected by the larger ones.

Frequency distribution no. 6 seems to represent nebkhas or shrub coppice dunes consisting of a coarser bulk and the finest sands trapped by vegetation.

Frequency distribution no. 7 presently cannot be correlated with dunes or sand sheets. (The bimodality is discussed in Besler (1996).)

Frequency distribution no. 8 is very characteristic of young dunes of various types derived from water-lain deposits. The high and narrow peak is comparable to active crests of older dunes (no. 1) but it is still situated in the finer fraction 0.063 – 0.125 mm. These depositional sand types are discussed in detail in Besler & Pfeiffer (1993).

The sand classification by grain size distribution is corroborated by differences in other properties of the sandstones like friability (lowest in fluvial deposits), salinity (lowest in aeolian deposits), and carbonate content (highest in fluvial deposits). The heavy mineral analysis especially corroborates the sand classification because there is a strong correlation

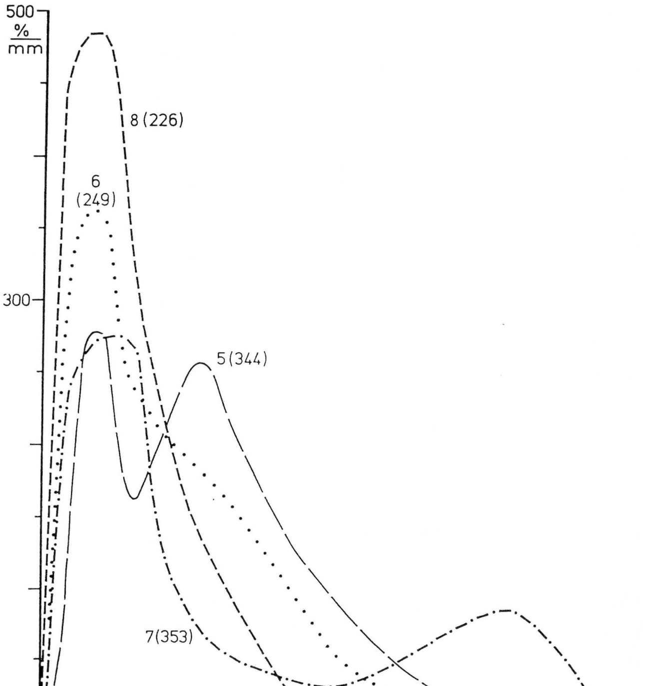

Figure 3 Frequency distributions of grain size in Tsondab Sandstones characteristic of sand types: 5: deflated dune, 6: nebkha, 7: not typical, 8: young dune. Numbers in brackets give the sampling sites in Figure 1.

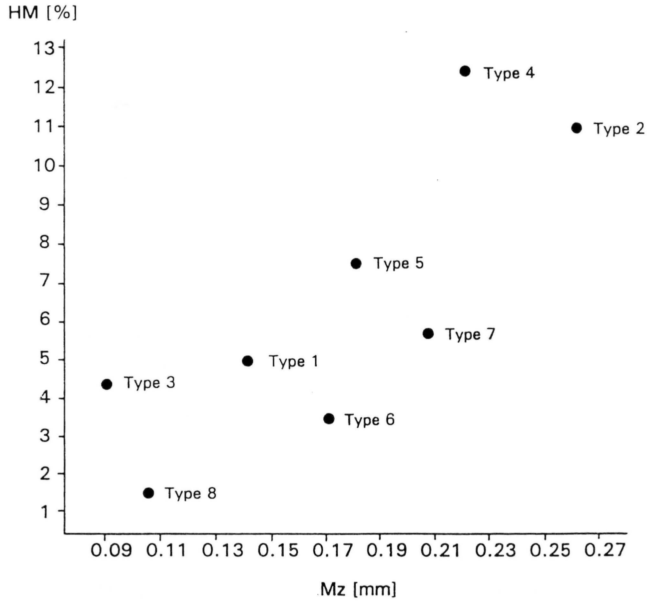

Figure 4 Total heavy mineral content and mean grain size of the Tsondab Sandstone.

between total heavy mineral content and mean grain size (meaning sand type); both qualities reflecting the stage of winnowing (Figure 4). The highest heavy mineral content is found in strongly winnowed sands like inactive dunes or flanks of dunes and older barchans. In barchan dunes there is even a distinct correlation between increasing heavy mineral content and decreasing curve shoulder, which means with increasing age. The lowest heavy mineral contents are found in source materials like fluvial deposits, nebkhas, and young dunes (rare). The correlations are discussed in detail by Besler & Pfeiffer (1993).

Figure 1 shows the spatial distribution of these granulometric sand types in the Tsondab Sandstone. The southern palaeo-erg seems to have been dominated by older barchan dunes. According to different stages of curve shoulders in the frequency distributions these barchans become progressively older towards the south. Barchan dunes are also indicated by crescent structures in the sandstone. In the northern palaeo-erg, the assemblage of active crest sands, inactive (flank) sands, and deflated (plinth) sands provides some evidence for longitudinal dunes. Where only active dune crests are found, they could also belong to transverse dunes or mature barchan dunes (but younger barchans than in the south). Therefore, this distribution is in accordance with Ward's (1988a) assumption. Star dunes cannot be distinguished from longitudinal or linear dunes by their granulometry because they contain the same granulometric sand types (Besler, 1996). Fluvial deposits are only found at the margins and are more deflated in the south. This supports Ward's reconstruction of the palaeo-environment in his figure 20 (Ward, 1988a) with fluvial deposition in the Tsondab Sandstone from the east. The point should be stressed, however, that as a granulometric sand type, the fluvial deposits had already been influenced by winds (deflation). Therefore, they are not strictly comparable with Ward's fluvial facies. Coarser material, as is found today in the interdraa valleys, was not found in the sandstone. This indicates a subdued topography: most probably the palaeo-erg was modelled by dunes and not by megadunes or draa, because, in most ergs, pebbles are also found in the large interdraa valleys. In this respect, the palaeo-morphology differs from the palaeo-dunes of lower Miocene age in the Rooilipel area north of the Orange River where concentrations of microconglomerates are characteristic of ancient interdune deflation surfaces (Pickford & Dauphin, 1993). On the whole, the wind regime in the palaeo-erg before planation seems to have been very similar to the modern one — prevailing winds from south to west and decreasing velocities towards north (Besler & Pfeiffer, 1993).

The whole Tertiary system, however, is much thicker (at least about 200 m) than the part studied here. Therefore, dune fields may be 'stacked' upon each other, or may sit on water-lain deposits in the lower parts. The system was also more widespread than the modern Namib Erg as the edges were cut off by the Kuiseb River in the north and the Koichab River in the south. Arenaceous deposits similar to the Tsondab Sandstone are found outside the erg in many places from the Orange River in the south to southwest Angola (Ward, 1987).

Dune sand consolidation and sand sources

The main matrix constituents are calcium carbonates and zeolites. Zeolite crystals — mostly phillipsite — are abundant in many samples. Zeolites, according to Turner (1980), seem to develop from the solution of volcaniclastics in alkaline and saline pore-waters. Within the range of zeolites, phillipsite seems to need less time for formation. In the Tsondab Sandstone phillipsite crystals have grown only on etched surfaces of pyroxene grains. Pyroxene is the dominant heavy mineral in most samples (Table 2); phillipsite is also abundant. Dickinson & Ward (1994) mention heulandite as one main cement in their sandstone samples. The distinction between the zeolites heulandite and phillipsite is difficult. But the twin crystals and the large-angle optical axis found for the zeolites in the samples provide evidence for phillipsite (60 – 80°) rather than heulandite (0 – 34°).

Much information on consolidation processes is provided by thin-section analysis. The quartz grains are more or less coated with clay stained by iron oxides, which was identified as iron-rich smectite by Dickinson & Ward (1994). In some samples, many quartz grains show cavities characteristic of etching in an acid environment and dark red goethite-like fillings. The whole grains then are coated by lighter red clay-iron oxide layers which unconformably cover the fillings. The following outer clay coatings are grey. The intergranular voids are filled with partly crystallized calcite. These samples also contain many rounded quartz grains as well as grains of calcite, marl, siltstone, and volcanites (for example nos. 137 and 226).

The following sequence of processes is suggested from these observations. These sands were partly derived from eroded lateritic material in accordance with the detritus model of the Simpson Desert (Turner, 1980). After fluvial deposition and aeolian modelling, the coatings formed by infiltration of clay particles in a first stage of continental red-bed diagenesis. This is not contradicting Ward (1987), who suggested a source of arenaceous sediments moving inland from the continental shelf. It only means that, in the upper parts of the Tsondab Sandstone, fluvial input from the east was also important. In his reconstruction of the palaeo-environment in the central Namib Desert during Tsondab times, Ward (his figure 20, 1988a) shows a fluvial facies of the Tsondab Sandstone Formation along the eastern Kuiseb River and its tributaries and along the Tsondab River. These fluvial deposits were also source materials for the aeolian facies under discussion.

In all samples, the unstable heavy minerals (pyroxene, green hornblende, and garnet) are still abundant and relatively unaltered. The feldspars are not corroded. Contrary to Dickinson & Ward (1994) no dissolution voids could be detected. With the exception of phillipsite, there is no evidence for authigenic silicate minerals. The zeolite crystals seem to have grown after the formation of the clay coatings when the porewaters became more alkaline. The crystals show no traces of corrosion. The change in coatings (from red to grey) and calcite precipitation indicate a progressively arid environment (Besler & Pfeiffer, 1993).

Fluvial input is also indicated by the spatial distribution of heavy minerals in the sandstone. For example, a high percentage of hornblende (> 15%), as is found in the modern Kuiseb deposits (Lancaster & Ollier, 1983), is also found in the Tsondab Sandstone near Tsondab Vley (no. 162) and near Tsauchab River (no. 388). Whereas the majority of sandstone samples show hornblende values < 8%, values ≥ 10% are found in sandstones near Narabeb (no. 6), Lost Valley (no. 156), Dieprivier (no. 90, 217), and Lüderitz (no. 300), which are near river courses (see Figure 1 and Table 2). This does not seem to be a random distribution, but indicates a fluvial facies of the Tsondab Sandstone as the source material along the Tsauchab River and perhaps along the Koichab River. The sandstone exposures here are too small to enable analysis of the stratification. These deposits have already been worked by winds and, according to their granulometry, partly incorporated into dunes (e.g. no. 90). The Etjo Formation quartzite (Karoo Sequence) on the Gamsberg (no. 202) has a very similar heavy mineral assemblage, including large amounts of hornblende and clinopyroxene, the latter being dominant in most sandstone samples. The heavy-mineral relation between Tsondab Sandstone and Etjo quartzite seems to be even more significant than between Tsondab Sandstone and shelf sediments. Unfortunately, only qualitative values are given by Lancaster & Ollier (1983). Sandstones of a Karoo sequence similar to the Gamsberg quartzite were already suggested as source material for the Tsondab Sandstone because of their similar quartz grain properties by Besler & Marker (1979).

Support for a rather short-distance fluvial transport is also provided by quartz grain shapes. In the majority of sandstone samples subangular quartz grains are dominant, whereas littoral sands are better rounded (Rogers, 1977). Indeed, a high percentage of rounded quartz grains is found in sandstone samples from near Conception Bay (no. 241), near Meob Bay (no. 249), from west of Uri Hauchab (nos. 353 and 354), and from north of Agate Beach (no. 282).

Planation problems

The wetter period of diagenesis should have been the time of planation, if corresponding to Ward's (1987) semi-arid Karpfenkliff fluvial phase in the Miocene or the pluvial phase in the revised model of Ward & Corbett (1990). But apart from the northern surface west of the Naukluft Mountains, there is no evidence for fluvial planation. The question is: what happened to the dunes?

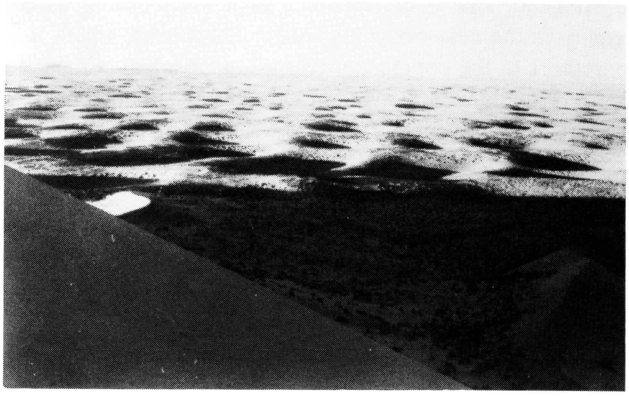

Figure 5 Looking from a 100 m-high dune situated on the sandstone rim near the Koichab River across the southeastern extension of the Namib Erg (mountains at the horizon). Note the very subdued and very regular dune pattern with scattered (grass) vegetation.

Perhaps the actualistic approach provides an explanation. In the eastern parts of the modern Namib Erg actual planation by increasing vegetation can be observed. The scattered tufts of herbs and grasses in the lower moister parts between dunes trap sands and thus reduce the topography. The southeastern extension of the erg (Figure 5), which receives 100 – 150 mm of precipitation, may serve as a model: a level plain is slowly forming.

However, another problem arises: the land surface below the erg has the same gradient as the Namib Plain outside the erg (1%). This could not have been achieved by planation caused by vegetation. The granulometry of the Tsondab Sandstone provides an additional argument against this hypothesis, as most grain size distributions are characteristic of active dunes rather than vegetated sands. The solution may be tectonic tilting of the Namib related to Late Tertiary epeirogenic uplift of the eastern part. Unfortunately there is no clear evidence for this tectonic event. On the other hand, it is possible that the dune topography of the palaeo-erg just before planation was already sitting on an inclined surface which was the product of a former fluvial erosion phase. It may well be that the Tsondab Sandstone is not an aeolianite throughout, but contains fluvial facies in the lower parts which are not exposed today.

In this context, it is of interest that in the Neogene aeolianites in the southern Sperrgebiet immediately north of the Orange River, a conspicuous planation surface was observed, covered by thick layers of water-lain silts (Senut *et al.*, 1994). According to the biostratigraphy, this surface separates the poorly fossiliferous lower aeolianite from the richly fossiliferous middle aeolianite. A Lower-Miocene age was assigned to the lower aeoliante, and an early Middle-Miocene age to the middle aeolianite. These ages place the erosion surface at the change from Lower to Middle Miocene and thus within the pluvial phase (Ward & Corbett, 1990). But whereas the deposition (and consolidation) of aeolianites in the southern Sperrgebiet continued intermittently during the Miocene and Post-Miocene, only erosion seems to have occurred in the Tsondab Sandstone until the pedogenic phase in the late Middle Miocene. This is corroborated by a study of depositional porosity in the near-surface Tsondab Sandstone, which leads the authors to the conclusion that no mechanical compaction occurred (Dickinson & Ward, 1994). If any silts had possibly been deposited on the surface they were eroded by wind and carried away. Later in the Pliocene, the accumulation of the Sossus Sand Formation began, but contrary to the Post-Miocene aeolianites in the southern Sperrgebiet, no consolidation seems to have occurred. Post-Tsondab Sandstone deposits including aeolianites are only recorded outside or marginal to the Namib Erg (Ward & Corbett, 1990).

At least one sample listed in Table 1 most probably represents a post-Tsondab Sandstone deposit. No. 249, a very friable, grey aeolianite with an extremely high carbonate content, containing shell fragments, was sampled southeast of Meob Bay immediately below lagoonal deposits. The elevation was 5 m higher than outcrops of the red Tsondab Sandstone (no. 246) in the vicinity (Besler & Marker, 1979, their figure 2d; Besler, 1980, her figure 2). Unfortunately, the contact between the grey and the red sandstone was covered by dunes.

Considering the planation discussed above, the southern part seems to be a pure erosion surface without any trace of deposition. This would explain the gradient as well as the truncation of dunes which most probably had been consolidated before.

Ward & Corbett (1990), in discussing why no pedogenic calcretes formed during the earlier stages of the pluvial phase, give a choice of either conditions being too wet or erosion being too vigorous. From observations on the surface below the Namib Erg, the conclusion may be drawn that even during the pedogenic phase the conditions were too wet or too dry for the formation of calcretes. Eitel (1993; 1994) argues that the formation of widespread and massive calcretes (2 – 15 m) was only possible because the carbonates supplied by earlier chemical weathering of carbonate-rich schists were caught in the system because of the primarily endoreic drainage into the Kalahari basin and the increasing aridity after the establishment of the discharge into the Atlantic Ocean. Very wet conditions would have lead to carbonate dissolution and export into the ocean. Therefore, it seems more reasonable to suggest vigorous erosion in a semi-arid climate. During the pedogenic phase, the Tsondab Sandstone surface most probably was too dry because airborne carbonates certainly were available for calcrete formation.

Significance of the Tsondab Sandstone for the Namib Erg

The first dunes of the Quaternary erg may even have developed from alluvial deposits on the surface before river incision in the late Tertiary. Blown sands were invading the Kuiseb Valley in the early to middle Pleistocene or even Pliocene and are preserved as aeolianite wedges in the Oswater Conglomerate (Ward, 1987; 1988b; Ward & Corbett, 1990). They differ from the main bulk of draa sands derived from dissected Tsondab Sandstone after river incision and river blocking (Besler, 1980). The aeolianite in the Oswater Conglomerate was subjected to sedimentological analysis and compared with modern Kuiseb sands, draa sands, and Tsondab Sandstone in the vicinity (Besler, 1991). The dominance of rounded quartz grains in the aeolianite is comparable to the nearest draa sands, but was not found in the sandstone or the Kuiseb sand. The sands with rounded grains seem to have been the oldest deposit on the Tsondab Sandstone surface. On the other hand, a rather high percentage of hornblende (23%) in the heavy-mineral assemblage of the aeolianite provides some evidence for intermingling with fluvial deposits of the ancestral Kuiseb. This corroborates Ward's (1988b) suggestion of a braided, ephemerally flowing river.

The point should be stressed that the Pleistocene longitudinal draa in the northern erg cross calcrete and pebble surfaces which provide no sands. The source of these interior sands is seen in large alluvial fans of an endoreic final stage of Tsondab and Tsauchab after river incision (Besler, 1980). As the southern ancient river systems were smaller, less sandstone was eroded and less sand provided for the — here lower — draa.

This scenario does not contradict Rogers (1977, quoted in Besler, 1980, p. 52) who demonstrated that the southern Namib Erg near Lüderitz is supplied with Orange River sands via two chains of barchan dunes forming on beaches near Chamais Bay and between Prinzenbucht and Elizabeth Bay. Littoral sands as one source in the southwestern and coastal parts of the erg are mentioned in Besler (1980), but Rogers also stated that his study did not concern the Namib north of 25°S.

In their paper on sand sources for the Namib Sand Sea, Lancaster & Ollier (1983) concluded that the main bulk of sands was derived from offshore or coastal sources from the analysis of grain size parameters and heavy minerals at twenty six localities in the sand sea. The spatial variations of grain size parameters in dune crest sands (Lancaster & Ollier, 1983, their figure 2) are shown by lines separating provinces of different values and suggest gradual changes. In the coastal and in the eastern part of the erg, some of these lines are not reasonable because no sample sites exist in the marginal parts. In other areas, only one sample locality was the base for the lines.

Besler (1980, p. 49 and diagram 1), using fifty dune crest sands alone in the northern erg, has shown that there is no gradual variation in mean grain size and standard deviation from west to east, but there are sudden changes in mean grain size related to dune types. Here again, the point was stressed that various sand sources should be considered: coastal, fluvial, and the Tsondab Sandstone. The close relationship between dune types and mean grain size is also demonstrated in Figures 2, 3, and 4. Abrupt changes to smaller and again to larger mean grain size were also found in dune crest sands along a south–north transect (Besler, 1980, diagram 4: > 50 samples). There are also considerable variations in shape and surface texture of quartz grains which indicate different sand sources. Whereas subangular-frosted to rounded-frosted grains are dominant north of Lüderitz, and thus agree with Rogers' analysis, rounded-frosted and subangular-clear or polished grains are dominant in the southeastern erg. In the interior and the northern sand sea, clear grains are even more abundant, opposing a long-distance aeolian transport (Besler, 1980, map 11). To sum up, there is not much evidence for the hypothesis that the main bulk of the draa and dune sands has been derived from the coast.

Lancaster & Ollier (1983) examined three samples of Tsondab Sandstone and got the 'overall impression that the sandstone does not seem to be a likely source' for the dune sands. In fact, most of the heavy-mineral phenomena mentioned by them could be explained by local Tsondab Sandstone being an additional source for the dune sands. Clinopyroxene is not only the dominant heavy mineral in the dune sands (Pfeiffer, 1991), but also in the Tsondab Sandstone (Table 2). At most localities where garnet in dune sands is dominant, the Tsondab Sandstone in the vicinity has exceptionally high garnet contents (23 – 77%). In their discussion on the possible sources, Lancaster & Ollier (1983) state that the rivers draining the Great Escarpment could not have supplied the dune sands because of their hornblende-rich sediments. In fact, the dune sands in the vicinity of Tsondab Vley, Diepriver, the Nam, and the Koichab River show high hornblende values (15 – 62%), contrary to the sands of the interior erg (Pfeiffer, 1991 and additional analysis).

On the other hand, the heavy-mineral assemblage of inner shelf sediments north of the Orange River, quoted in Lancaster & Ollier (1983), is not very similar to the Namib Erg assemblages, not even in the coastal part. Apart from garnet and the ubiquitous pyroxenes, neither rutile, tourmaline, nor staurolite are of any importance in the dune sands. The authors also included the inner shelf between the Orange River and the Olifants River where a different heavy-mineral assemblage was reported. If the heavy-mineral suites north and south of the Orange River are different today, then there has obviously not been much sediment transport towards the north across the Orange River delta.

Field observations at selected sites (Tsondab Vley and Uri Hauchab) and sample comparisons have shown that, during the decomposition of the sandstone and the aeolian reworking of the sand, the analytical properties gradually change in a characteristic way: mean grain size and sorting increase, and the salinity is constantly being reduced, because diagenetic particles and smaller grains are blown out. Constant aeolian winnowing leaves coarser and heavier grains behind. Therefore, the heavy-mineral content is increasing. During reworking, the grain coatings are abraded, and the sand colour becomes lighter. Only shape and surface texture of quartz grains are not significantly altered.

The sandstone samples and the draa or dune sands sampled in their vicinity, were compared using all analytical properties listed in Tables 1

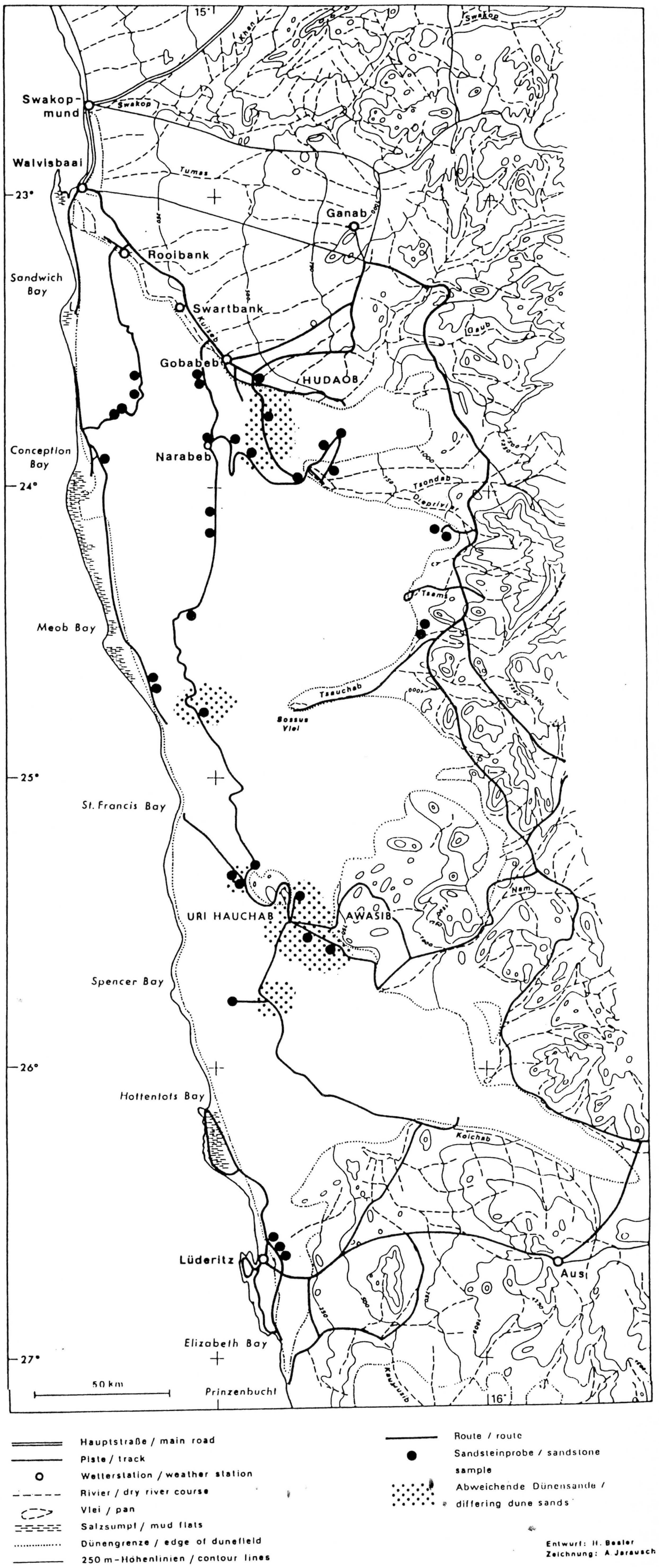

Figure 6 Localities where dune sands of the Namib Erg differ from the underlying Tsondab Sandstone.

and 2. The rules were followed that a sand derived from the sandstone should be coarser, better sorted and less saline, and should have a higher heavy-mineral content (Pfeiffer, 1991) and less coatings. Of course, the quartz-grain shape should be the same in both the sandstone and the sand. The surface texture, however, could have changed if fluvial processes had been involved in sandstone erosion and sand transport, even over a short distance. Therefore, the surface texture, being an unreliable indicator, was not considered.

In fact, the comparison of sandstones and dune sands shows that only in a few places could the sand not have been derived from the sandstone outcrops in the vicinity (Figure 6). To the northwest of Tsondab Vley, the dominance of rounded quartz grains in the sands, and the lower garnet content near the Kuiseb, are not compatible with a sandstone source. Farther west, the sandstones also contain about 50% rounded grains (Table 1) and are similar to the sands. To the west of Sossus Vley, the dune sand has a lower mean grain size and a lower heavy-mineral content than the sandstone. The greatest difference is found in the area between the Uri Hauchab and the Awasib Mountains. Here, the dune sands partly have a lower mean grain size, a lower heavy-mineral content, and more coatings than the sandstone. There is also a dominance of rounded grains in the sands (also south of Uri Hauchab). At the western edge of the Uri Hauchab, only the garnet content in the sands is lower than in the sandstone.

It seems unlikely that the great similarity between dune or draa sands and the underlying sandstone is a random phenomenon. The Tsondab Sandstone seems to be an important source for the dune sands. This does not contradict the importance of littoral sands as a source for the dunes between Lüderitz and the Uri Hauchab. On the other hand, the high amount of clear or polished quartz grains to the west of Sossus Vley and Nam Vley and in the northwestern erg (Besler, 1980, map 11) cannot have come from the coast by aeolian transport. These grains also cannot have been derived from the Tsondab Sandstone without fluvial erosion and transport. Therefore, three main sources of sand for the Namib Erg are suggested (Besler, 1980): littoral, fluvial (spread out in alluvial fans), and sandstone decomposition. Sandstone weathering would have occurred mainly after river incision because more surfaces are exposed in a rugged topography.

Conclusions

The granulometric analysis of the near-surface Tsondab Sandstone reveals some aspects of the morphology of the palaeo-erg in its last stage before planation. The southern part seems to have been dominated by barchan dunes after a long period of migration, whereas in the northern part longitudinal dunes were abundant. The grain size distributions and the stratification provide evidence for prevailing palaeo-winds from south to west with northward decreasing velocities. According to the analysis of heavy minerals and quartz grains, various sand sources seem to have been important: littoral sands in the coastal part and fluvial deposition from the east. Because of the great similarity of the heavy-mineral assemblage in the Etjo Formation quartzite on the Gamsberg, this sedimentary rock is suggested as one source material for the Tsondab Sandstone.

Dune sand consolidation occurred by clay infiltration, the growth of zeolite crystals (phillipsite), and carbonate cementation in a progressively arid environment. The Miocene planation surface in the Tsondab Sandstone has never been completely buried. Dissection occurred only along the eastern margin and farther west along the Tsondab and the Tsauchab rivers. Large parts of the Miocene surface are preserved without subsequent geomorphic modification.

The first dunes of the Namib Erg most probably developed in the Pliocene. Three main sources of sand for the modern draa and dunes are suggested from quartz grain properties and heavy mineral distribution: littoral sands along the coast, especially to the north of Lüderitz; alluvial deposits in the interior erg, especially to the west of Sossus and Tsondab Vley; and decomposed sandstone in the dissected eastern parts (see Figure 1). The alluvial fans, of course, also contained polished sands derived from sandstone erosion. The Namib Erg, in large parts, has inherited the sand properties from the Tsondab Sandstone which is, therefore, considered to have been an important source of sands for the Namib Erg.

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