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EVIDENCE OF PAST CLIMATIC CHANGE IN THE NAMIB DESERT[1]

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Abstract

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A preliminary survey of some areas of the Central and Northern Namib Desert was undertaken in order to identify geomorphic and sedimentary features that could potentially provide information on past climatic change in the region. Wherever possible, samples were collected for radiocarbon dating. The visits to the Skeleton Coast area were especially revealing: practically every river valley in this tract shows a sequence of terraces and deposits that would warrant a detailed study. In all, about 120 new radiocarbon dates were obtained for the region. These have supplied a wealth of individual results and, collectively, have enabled the construction of a tentative chronological sequence of the changes in climate for the past 40,000 yr. Three periods of increased aridity in the hinterland, but with decreasing intensity are postulated: during the Last Glacial Maximum, the early Holocene, and between A.D. 1200 and A.D. 1600. The Inter-Pleniglacial up to 23,000 yr B.P., the Late Glacial, and the period between about 4000 yr B.P. and 1200 yr B.P., on the other hand, were more humid than today, also with decreasing intensity. Other indicators of past climate were also identified, but since they lie beyond the range of radiocarbon dating, they cannot as yet be placed in a chronological context. Of significance is the fact that convincing evidence was obtained for climatic change within the last millennium and, specifically, that rainfall is found to have been increasing since the 16th century.

Introduction

The Namib Desert stretches along the west coast of Southern Africa for a distance of about 2000 km, from just north of the Olifants River in the Cape Province of South Africa (31°S) to beyond Moçamedes in Angola (14°S). Laterally it extends from the Atlantic coast to the base of the inland high plateau — a distance of not much more than 100 km in the central region and even less elsewhere.

The climate is warm-temperate (with light frost in winter) and hyper-arid along the coast to arid along the eastern margin. In the Central Namib (Fig.1) the mean annual rainfall varies from 12 mm at Walvis Bay to about 100 mm below the escarpment. The virtual absence of rain along the coast is due to the low surface temperature of the southeast Atlantic ocean caused by extensive upwelling. The cold sea does, however, have the effect that fog frequently moves in over the desert to produce some additional precipitation. Such events occur on 60 to 70 days a year on the coast at Swakopmund, where they produce a total of some 34 mm precipitation annually. These figures decrease inland to 37 days and 31 mm at Gobabeb, which is situated 57 km from the coast, and to practically zero at the base of the escarpment (Lancaster et al., 1984).

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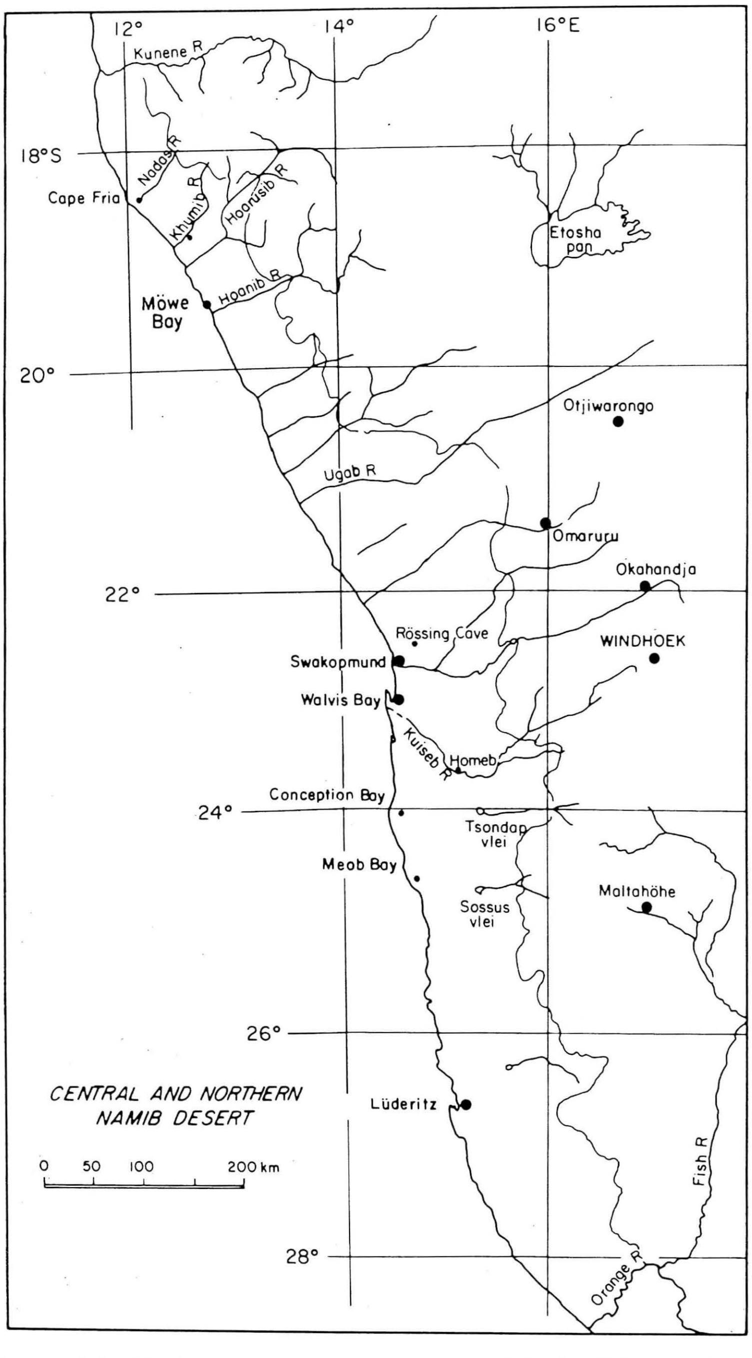

Fig.1. The Central and part of the Northern Namib Desert with some of the localities mentioned in the text. The thin continuous line parallel to the coast demarcates the approximate inner margin of the desert.

Over the entire stretch of coastline only two perennial rivers, the Orange River in the south and the Kunene River in the north, traverse the desert to flow into the ocean. There are, however, a number of dry river courses that on occasion carry floodwater from the inland plateau down to the sea. These rivers tend to have an unusual convex profile near the coast

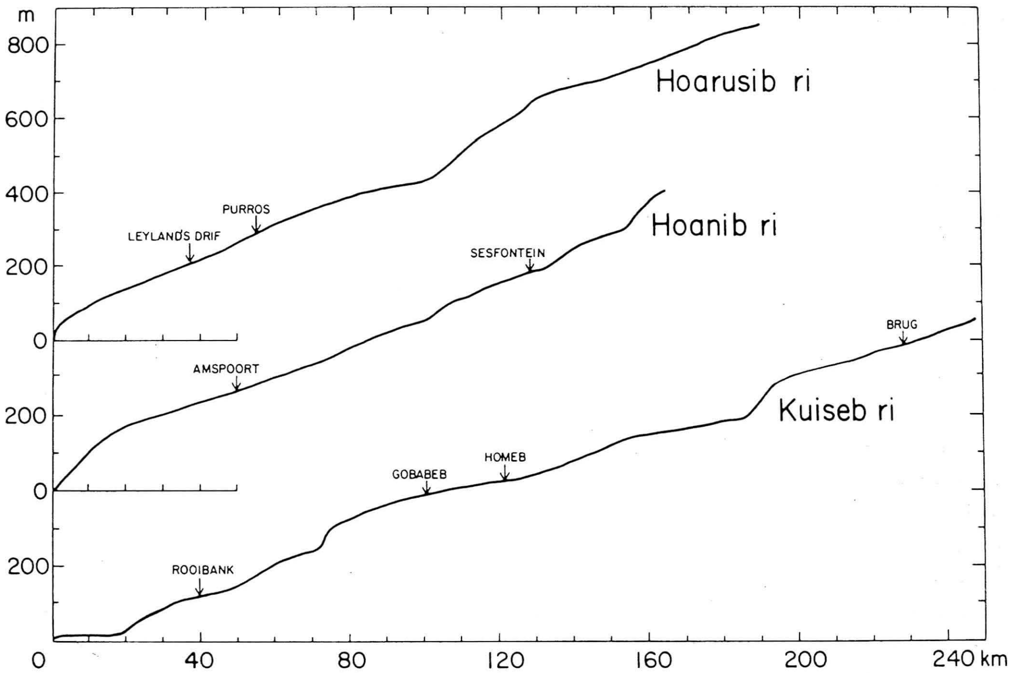

Fig.2. Profiles of three of the rivers traversing the Namib Desert, showing the characteristic convex shape near the coast.

(Fig.2), which is due to the fact that the amount of water they carry decreases as the floods move downstream and sink into the sandy riverbeds. A further consequence of this flow pattern is that the rivers tend to drop their loads along a specific stretch of riverbed which corresponds to the average reach of the floods. Relatively small changes in flood intensity caused by variations in precipitation thus lead to a redistribution of sediment along the river course, and relicts of these fluvial sediments document such changes rather accurately.

Due to the extreme aridity of the Namib Desert relict features that reflect past environmental conditions are especially well preserved. This holds good for geomorphic occurrences such as fluvial silt deposits which often show practically no secondary alteration by weathering, as well as for such features as dead trees that hardly decay and can remain standing upright for many centuries. Consequently the desert contains abundant evidence relating to climatic conditions in the past and, provided that these features can be interpreted correctly and also dated, a record of climatic change during the more recent past as well as during the Upper Pleistocene could gradually be reconstructed for the entire region. In fact, the potential of the area for providing palaeoenvironmental data is probably unique on the Southern African subcontinent.

In the warm-temperate environment of the Namib rainfall is more important than temperature in determining local conditions. In addition alluvial deposits in the main river valleys relate directly to run-off from above the inland escarpment, so that here, too, the rainfall pattern is the determining variable. It is to be expected, therefore, that evidence of past climates will, in the first instance, reflect precipitation and "wetness" and that temperature changes will be less apparent. This is no drawback but rather an advantage, since information on changes in precipitation is more difficult to come by.

Hitherto geomorphologic investigations in the Namib have been few and far between and much of this large expanse is still completely unknown. The purpose of the present paper is to report briefly on some of the features of palaeoenvironmental significance that have been encountered in the Central and Northern Namib desert, and on the radiocarbon dates obtained on material from the deposits. These data will then be combined to produce a tentative model of the changes in "wetness" that occurred in and beyond the coastal desert over the past 40,000 yr.

Comments on method

Field work and interpretation

In the course of the years several short field trips were undertaken to the Namib to locate and record sedimentological, pedological and other environmental features which reflect past climatic conditions and, where possible, to collect material for radiocarbon dating. The visits were concentrated on the Kuiseb River valley and the adjacent southern sand-sea on the one hand, and the Skeleton Coast between the Ugab River and Cape Fria on the other (Fig.1). In the northern region remnants of fossil silt deposits were observed in all the dry river courses, but it was also obvious that they are of widely different ages. In several instances these fluvial sediments can be correlated with at least two distinct colluvial terraces which are the result of local sheet wash and thus represent increased local runoff (Rust, 1987; Rust and Vogel, 1988).

Much of the datable material was obtained from fluvial sediments, the palaeo-climatic interpretation of which needs careful consideration. In general we ascribe the aggregation of fine-grained, horizontally bedded silt deposits to periods of low stream competence and therefore decreased runoff from the hinterland, viz. drier conditions in the upland regions and, especially, drier conditions than during subsequent phases of incision. Strongly cross-bedded, coarse or unsorted flood deposits may, on the other hand, represent an entirely different set of circumstances, including single energetic floods of little long-term climatic significance. To gain more certainty with regard to these interpretations, detailed studies of each of the individual sediment bodies would need to be undertaken, and until such time the conclusions are necessarily preliminary.

The climatic interpretation of pedogenic calcrete occurrences in the desert also poses a problem. The stable isotope composition of such carbonate usually suggests that vegetation played only a small role in its formation. At present it is felt that these calcretes were formed towards the end of relatively moister local conditions.

Radiocarbon dating

In those cases where plant material such as wood could be found in relevant situations, the radiocarbon dating posed no problems. For the most part, however, recourse had to be taken to less reliable sample material such as calcified crusts or calcretes, and here the interpretation of the radiocarbon dates needs special care. In the first instance, calcium carbonate precipitated under fresh water conditions can have an initial apparent age of as much as 2000 yr, so that uncertainty exists as to what adjustment needs to be made to the measured date to account for this effect. For reasons given elsewhere (Vogel, 1982) 1000 yr are subtracted from the apparent ages obtained on such material, but an uncertainty of ± 500 yr must, in general, be attached to these estimated ages. Secondly, the host material may already contain lime of a much older age and the sample thus be of a mixture. In the dating of fluvial silts, for instance, care must be taken to sample only obvious calcified crusts that formed during accumulation of the sediment. Fortunately such desiccation crusts were found to be reasonably common in low energy silt deposits. These crusts incidentally also show that such sediments are gradual accumulations and not single-episode flood deposits that have less value as climatic indicators.

Field observations and dating

Some of the geomorphologic features that were encountered and that are relevant to this study will be discussed briefly together with the radiocarbon dates obtained.

Kuiseb River Valley

Due to its relative accessibility the Kuiseb has been studied much more thoroughly than the other river valleys in the Namib. The known deposits in the area are enumerated and references to earlier work are given by Ward (1984). Of relevance here are the following:

Oswater conglomerate

Remnants of this fluvial sediment are found in the river gorge from between Gobabeb and Homeb (Fig.2) all the way to the base of the escarpment (Ward, 1982, 1988). In the vicinity of Homeb they form the "40 m Terrace" discussed by Rust and Wieneke (1974, 1980). This cobble/pebble conglomerate was securely cemented with calcium carbonate at some stage(s), subsequent to deposition and prior to its re-excavation. A number of dates have been run on this carbonate cement with the following results (adjusted ages):

Pta-1493	Oswater congl. 8a, Homeb S bank, top		28,400 yr B.P.
Pta-2355	Oswater congl. 8b, Homeb S bank, top		27,900 yr B.P.
Pta-2329	Oswater congl. 8c,	fr. 1	33,500 yr B.P.
Pta-2330	Homeb S bank, − 14 m	fr. 2	34,600 yr B.P.
Pta-2655	Oswater congl. 9,	fr. 1	28,100 yr B.P.
Pta-2656	Quormeb N bank, top	fr. 2	37,200 yr B.P.
Pta-2653	Oswater congl. 10, Quormeb N bank, base		46,800 yr B.P.

The dates appear to be consistent, decreasing from the bottom upwards, but the large difference between the ages of the outer fraction (fr. 1, Pta-2655) and the inner fraction (fr. 2, Pta-2656) of the top Quormeb sample clearly shows that there was more than one episode of calcification. Thus, the original cementing of the conglomerate must be assumed to pre-date 46,800 yr B.P. (Pta-2653). The final down-cutting and removal of the valley fill, however, could possibly have taken place around 30,000 yr B.P.

Hudaob calc-tufa

At Great Hudaob, 55 km upstream of Gobabeb, a tufa deposit occurs on bedrock on the S bank of the Kuiseb canyon (Ward, 1984). It formed from seepage draining out of a small side gully, filled with consolidated Tsondap sandstone, and clearly documents more humid conditions locally. Radiocarbon dating produced the following results (adjusted ages):

Pta-4521	Hudaob tufa, top	9870 yr B.P.
Pta-4593	Hudaob tufa, − 1 m	34,000 yr B.P.
Pta-4597	Hudaob tufa, tip of tongue	30,100 yr B.P.

Most of the deposit thus dates to 30,000–35,000 yr B.P., with some renewed activity at the end of the Pleistocene.

Some 10 km downstream, at Nata Gamtes, another small tufa tongue emerges from the N bank of the canyon. This also gave a Late Pleistocene date of 14,830 ± 130 yr B.P. (Pta-4515).

Homeb silts

Remnants of these fine-grained silts are preserved in embayments of the Kuiseb River gorge from Oswater/Homeb to Gomkaeb some 30 km upstream (Ward, 1984). Originally described as the Ossewater lake deposits (Rust and Wieneke, 1974), they are predominantly horizontally bedded with occasional low-angled cross bedding. At places small aeolian sand lenses interdigitate, and there are numerous levels with desiccation cracks and thin (1 cm) calcified crusts. The nature of the silt body thus indicates low energy deposition over a protracted period, probably under similar conditions as exist at Rooibank, close to the coast (Fig.2), where the river is dropping its load today. Radiocarbon dates on calcified crusts that formed during the evaporation of ponded water, of snails and, in one case, of interbedded plant material show that these sediments accumulated between ca. 23,000 and 19,000 yr B.P. (Vogel, 1982). At Homeb the silts extend to 37 m above the present riverbed. At the time when the valley was filled to this height, seepage water would have spilled over the south bank, and it is not surprising that a calcified reedbed, calcified root casts and termite nests in the dune streets south of Gobabeb all give radiocarbon dates of about 20,000 yr B.P. (Vogel and Visser, 1981; Vogel, 1982).

Natab silts

These silts occur at various places between Gobabeb and Homeb and indicate valley filling up to some 10 m above the present riverbed, representing a stage that post-dates the removal of the Homeb silt accumulation from the river channel. They are overlain by a thin layer of river pebbles, the Gobabeb gravels, which indicates an increase in energy of the floods prior to the final re-excavation of the channel to its present level.

At Homeb sandy silt deposited on the partly eroded Homeb silts gave an adjusted date of 9300 yr B.P. (Pta-2009, Vogel, 1982). At Gobabeb calcareous crusts and crack fillings from this silt body on the N bank gave the following adjusted dates:

Pta-3634	Natab silt. Gobabeb N bank, +10 m	4300 yr B.P.
Pta-3628	Natab silt. Gobabeb N bank, +9 m	4870 yr B.P.
Pta-3823	Natab silt. Gobabeb N bank, +8 m	5710 yr B.P.
Pta-3833	Natab silt. Gobabeb N bank, +7 m	8340 yr B.P.

At Natab itself two calc-crusts from the exposure on the N bank gave similar results:

Pta-3647	Natab silt. Natab N bank, +7 m	4200 yr B.P.
Pta-3642	Natab silt. Natab N bank, +6 m	5840 yr B.P.

Three other sites between Gobabeb and Homeb gave dates between 6100 and 3740 B.P. for root casts, a calc-kindl and a calcified stem in the silt levels.

Hoarusib River Valley

Four different fluvial silt deposits were observed in the lower reaches of the Hoarusib River. These are considered to be different members of the Hoarusib alluvium formation (Vogel and Rust, 1987; Rust, 1987).

The Clay Castles silt member

Some 20 km upstream remnants of the Clay Castles silts are preserved in the northern side valleys. These fine-grained horizontally bedded silts reach to as much as 70 m above the present riverbed and are at places overlain by the upper colluvial terrace of locally derived coarse material. They are extensively cemented by calcium carbonate and contain dunesand lenses locally.

The Leyland's Drift gravel member

At Leyland's Drift coarse cemented slope wash was deposited from the northern side valley at a stage after the Clay Castles silts had partially been eroded. A relatively humid phase preceded this valley filling since the surface of the Clay Castles silt is distinctly oxidized in places.

The Hoarusib Mouth silt member

At the mouth of the Hoarusib River an alluvial fan stretches some 5 km along the coast. This silt delta was deposited onto a Holocene beach and is at present being eroded away by the sea to form a cliff face up to 8 m high. The base of the deposit is coarse and cross-bedded with pebbles and remnants of silt blocks, while the upper layers are fine-grained and horizontally bedded.

The Young Terrace deposits

A lower 5 m silt terrace is intermittently present in the river channel all the way from the mouth to Purros, some 54.5 km upstream. It also extends into the side valleys, and on occasion contains blocks of Clay Castles silt, logs and branches.

In all, ten samples of calcareous material from the Clay Castles silts (Clay Castles silt member) were processed. These included calcareous crusts, calcified rootcasts, snails and calc-kindl, most of which represent post-depositional calcification.

Pta-3442	Clay Castles silt. Cl.Ca.valley, pedotubles	17,900 yr B.P.
Pta-3466	Clay Castles silt. Cl.Ca.valley, gypsum crust	29,700 yr B.P.
Pta-3537	Clay Castles silt. Cl.Ca.valley, snail shells	32,400 yr B.P.
Pta-4122	Clay Castles silt. Cl.Ca.valley, calc. sand	20,400 yr B.P.
Pta-4105	Clay Castles silt. Cl.Ca.valley, kindl	41,600 yr B.P.
Pta-3549	Clay Castles silt. Downstream, nodule	28,600 yr B.P.
Pta-3543	Clay Castles silt. Downstream, calc. silt	33,700 yr B.P.
Pta-3548	Clay Castles silt. Downstream, snail shells	38,200 yr B.P.
Pta-3490	Clay Castles şilt. Leyland's drift, calc. termite nest	15,000 yr B.P.
Pta-3815	Clay Castles silt. Leyland's drift, snail shells	30,200 yr B.P.

In this time-range the highest dates must be accepted as a minimum age for the deposit, especially when the nature of the samples is considered. It can therefore be concluded that the sediment body pre-dates 41.6 ka B.P.

The base of the silt fan at the mouth of the river (Hoarusib Mouth silt member) underlies a beach deposit which dates to 4850 B.P. (Pta-4301). A calc-crust and calc-kindl formed in drought cracks gave adjusted ages of ca. 4230 and 3060 yr B.P., respectively (Pta-3866, -3868). This deposit presumably represents a stage when the river flow was decreasing, with the result that the initial coarse cross-bedding was gradually replaced by fine silt.

Finally the Young Terrace that is represented over the whole lower reach of the river, from the mouth up to Purros, is reliably dated by plant material to between ca. 900 and 720 B.P. (Pta-3447, -3876, -3841, -3515, -4535). During this period the river established a ca. 5 m higher base level before the final incision of the present channel. Evidence for a period of downcutting between the stage of the Hoarusib Mouth silts and the infilling of this young terrace was not, however, actually observed.

Hoanib River Valley

The Hoanib River just south of Möwe Bay normally terminates in a large floodplain just inland of the 10 km broad dune barrier along the coast. Between the floodplain and Amspoort, 44 km from the coast, the river is at present excavating an 8 m channel into its own silt/sand deposits. These silts constitute the youngest member of the Hoanib alluvium formation, the Amspoort silt member, which has drowned the landscape over a broad stretch (Vogel and Rust, 1987; Rust, 1987). Three further fluvial members could be identified: at Amspoort the silts overlie the gravels of the Lower Terrace, derived from side valleys and backslopes, and called the Tsuxub gravel member. This in turn overlies a calcified basal conglomerate. Upstream of Amspoort the river is incised 1–2 m into fluvial sediment forming the Young Terrace in the valley. Further upstream at the junction of the Mudorib side arm, an 8 m high remnant of silty sands with calc-crusts, the Mudorib silt member, underlies slope deposit forming the Upper colluvial Terrace and thus pre-dating a local wet phase.

Four samples of calcified crusts in the Mudorib silt member gave apparent radiocarbon ages between 31,000 and 36,000 yr (Pta-3933, -4116, -4112, -4110). Although the dates are in stratigraphic order, they can only be considered as minimum dates in this time-range, and this stage of valley filling may chronologically equate the Clay Castles silts in the Hoanib River (see above).

A log buried in the Young Terrace of the Hoanib between Amspoort and the Mudorib gave a date of 1120 yr B.P. (Pta-3890), showing that these deposits are of the same age as the Young Terrace in the Hoarusib. An upright tree buried in 8 m silt below Amspoort gave a 16th century date (Pta-3880), showing that the Amspoort silt accumulation is sub-recent. The present erosion of these silts and their redeposition lower down in the flood plain suggest that river lengthening is actively in progress.

At the Hoanib Oasis, seaward of the dune barrier, elevated silt remnants dating to about 3900 yr B.P. (Pta-3912) document a stage when the river was more competent than it is today.

Khumib River Valley

At the mouth of the Khumib River in the north, a broad fluvial fan is at present being eroded by the sea to form a cliff up to 6 m high, stretching for 9.6 km along the shore, similar to that at the Hoarusib River mouth. This alluvial terrace can be traced tentatively up the river to beyond the Sarussas West Waterhole. The river channel is often on bedrock, although some calcified dunesand and gravel was observed at the mouth. The remnants of the alluvial terrace are mostly coarse and cross-bedded, indicating more energetic flow, different from the 5 m terrace deposit in the Hoarusib. At places more finely grained and regular sediment is also preserved, indicating that different generations of aggradation are present. At one such point, 5.8 km upstream, a log protruding from a 1.2 m silt face gave a date of 310±40 yr B.P. (Pta-4538), i.e. the same age as the logs in the Amspoort silts of the Hoanib River. At Sarussas West Waterhole calcified plant remains (calc-tufa) up to 10 m above the present bed indicate desiccation of a wet stretch at a time when the riverbed was at a higher level than today. Similar calc-tufa occurs at Okau Waterhole at the end-point of the Munutum River further north and above Karlova's house at Cape Fria (see below).

Calcified reedbeds

Along the coast south of the Kuiseb River fresh groundwater seeps into the sea at Conception Bay and at Meob Bay (Fig.1). Both at Conception Waterhole and on the inland side of the Meob Oasis remnants of a flat elevated surface, capped by an extensive calcareous crust with calcified reed (phragmites) stalks, provide evidence of an elevated groundwater table and vlei conditions. J. D. Ward has pointed out to me that the last interglacial (?) beach underlies the aeolian sands on which the reedbeds developed, thus giving a terminus post quem for the vleis. Radiocarbon analyses consistently give (adjusted) dates of between 10,700 and 11,600 yr B.P. for these calcified crusts (Vogel, 1982).

Calcified plant remains from three other sites in the northern region yielded similar dates: the beds above the Sarussas W Waterhole in the Khumib River, those at the Okau Waterhole at the endpoint of the Munutum River, and beds above Karlova's house at Cape Fria, date to 10,640 yr B.P., 11,780 yr B.P. and 11,930 yr B.P., respectively (Pta-3474, -3479, -3495, -3511, -3531). The striking similarity between these dates (ten in all) is taken as evidence for a regional episode of desiccation. This is further supported by some small-scale pedogenic calcrete formation in the Central Namib Sandsea and on the adjacent gravel plains: at Narabeb calcareous blotches, some 30 cm below the surface, give an (adjusted) date of 10,470 yr B.P. (Pta-3260); in the Lower Tsondap flats 10 cm of powder calcrete, 10 cm below the sand surface, date to 11,110 yr B.P. (Pta-3261); and the surface calcrete on the plains N of the Kuiseb River gives an age of about 9000 yr B.P. (Pta-3262).

Other calc-tufas in the Namib which also document a transition from more humid to drier conditions yielded higher (adjusted) ages, viz.:

Pta-3184	Koichab Pan, reedbed	fr. 1	22,800 yr B.P.
Pta-3185		fr. 2	22,300 yr B.P.
Pta-3528	Hoanib Oasis, reedbed		23,600 yr B.P.
Pta-3516	Khowaribschlucht, reedbed		24,900 yr B.P.
Pta-3186	Möwe Bay, calc-tufa	fr. 1	29,000 yr B.P.
Pta-3187		fr. 2	28,300 yr B.P.

Palaeoclimatic reconstruction

When the evidence gained thus far is considered together, the changes in climate since the Late Pleistocene in terms of 'wet' and 'dry' can be reconstructed tentatively. Here it must be pointed out that the environmental condition 'drier than today' refers to conditions in the hinterland and is not actually observable in the desert itself. Using mainly the data presented in the previous section, the climatic interpretation of our current observations will be reviewed in chronological sequence for that period accessible to radiocarbon dating, i.e. for the past 40,000 years.

Inter-Pleniglacial 40,000–23,000 yr B.P.

There appears to be general consensus that the Inter-Pleniglacial period of the Last Ice Age (Oxygen Isotope Stage 3), ending about 25,000–23,000 yr B.P., was more humid in the summer rainfall region of Southern Africa (Deacon et al., 1984; Deacon and Lancaster, 1988). In the Central Namib local humidity is documented by speleothem formation in the small Rössing Cave. Ten radiocarbon dates show that the cave sinter developed between 42,000 and 26,500 yr B.P., with no cavestone formation since (Heine and Geyh, 1984). The tufa deposit at Hudaob in the Kuiseb River gorge also indicates more local moisture. In addition there are several radiocarbon dates for calcified rootcasts and calcretes in this interval (Vogel and Visser, 1981; Rust and Vogel, 1988). In some cases, at least, these dates indicate more humid local conditions. The calcified reedbeds at Koichab Pan, Hoanib Oasis and Khowaribschlucht presumably date the end of this wetter phase. It thus appears that there is also good evidence for more humid conditions in the Namib Desert during Isotope Stage 3 than at any time since. There may, of course, have been dry spells in this rather long interval which have not been identified.

The Last Glacial Maximum

Evidence of climatic conditions during the Last Glacial Maximum is forthcoming from the Homeb silt deposits in the lower reaches of the Kuiseb River canyon (Vogel, 1982). At present the river is dropping its silt load in the vicinity of Rooibank (Fig.2) and the Homeb silts are interpreted as an indication that the floods from the upland had lower competence at the time and, therefore, reflect drier conditions above the escarpment. This interpretation holds good whether the silts are considered to have been laid down as an overbank deposit under conditions of low stream discharge (Ollier, 1977; Ward, 1984), as a river end-point deposit (Marker and Muller, 1978; Vogel, 1982), or as a result of damming by sand dunes (Rust and Wieneke, 1974) (see Deacon and Lancaster, 1988).

No equivalent of the Homeb silts was found in the northern river valleys, perhaps because our reconnaissance did not extend sufficiently far inland.

The Late Glacial

Subsequent to this massive infilling of the valley of the Kuiseb, the energy of the floods increased and incision set in again. The Homeb silts were removed extensively, also from the side valleys, so that only remnants remain in protected localities. This increase in run-off is also documented in the Lower Tsondab flats. Today the small Tsondab River terminates in the Tsondab Vlei some 84 km inland from the coast, but at 13,000 yr B.P. the river extended further to the west and deposited silt along this lower section of its course (Vogel, 1982). These low silts clearly document greater run-off into the Namib Desert during the Late Glacial. Renewed tufa formation in the Kuiseb River gorge at this time shows that there was also more moisture in the desert itself.

Good evidence for the end of this more humid phase is provided by the calcified reedbeds at several places along the coast. At both Meob Bay and Conception Waterhole shallow bedrock causes groundwater seepage from under the great dunefield to come closer to the surface, and while the groundwater level was high, reedbeds developed on the flat surface. A drop in the water-table at the end of the period caused desiccation and calcification of the surface between about 12,000 and 10,000 yr B.P. During the subsequent dry period wind erosion lowered the general surface, so that the calccrusts are now elevated some 4 m above the surroundings. The similar dates for calc-tufas at the three waterholes on the Skeleton Coast and for the onset of pedogenic calcrete formation in the central area indicate that the desiccation was a regional event. The evidence for more humid conditions in the Namib and adjacent upland during the Late Glacial thus corroborates the findings in the Western Kalahari (Deacon et al., 1984; Lancaster, 1989, this issue).

The Early Holocene

The Natab silts in the Kuiseb valley document a protracted dry spell, lasting from before 8300 yr B.P. to about 4200 yr B.P., during which river shortening occurred once more. The pebble layer on top of the Natab silts (Gobabeb gravels) presumably records the renewed increase in run-off, leading to the final incision down to the present base-level.

The silt fan at the mouth of the Hoarusib dates to the end of the dry spell, when the river was actively removing sediment from its catchment area and from along its course (e.g., fragments of Clay Castles silt).

The last millennium

Several features in the study area bear witness to climatic conditions during the last millennium (Vogel and Rust, 1987). The reliably dated Young Terrace deposits in the lower Hoarusib River and in the Hoanib River above Amspoort suggest locally wetter conditions which terminated at about 900 yr B.P. At the mouth of the Ugab River, infilling is also documented at this time.

Here again the hypothesis is that channel filling represents decreased flow and, consequently, drier conditions in the catchment area prior to the final down-cutting of these rivers to their present levels. A further indication of drying out is to be found at Sossus Vlei, the present end-point of the Tsauchab stream in the Central Namib. Here, between dunes to the south of the present vlei, a clump of dead *Acacia erioloba* trees, many still standing upright, became established on a silt surface. Radiocarbon dating has shown that at least one of them was growing by 950 yr B.P. and that they died between 700 and 600 yr B.P. (seven dates unpubl.), suggesting a drastic lowering of the groundwater table. Since then deflation of some 2 m has taken place in the northern section, and in one corner of the deflated surface a few acacias have established themselves again, possibly indicating a renewed rise in groundwater level under the vlei in recent centuries.

Finally it should be pointed out that all the rivers traversing the Central and North-Central Namib Desert are at present actively eroding their previously deposited sediments, also from the local side valleys. This suggests increased run-off in recent centuries, which may mean that rainfall conditions are actually improving. The current increase in run-off cannot be man-made, because agriculture is not practised on the upland and herding has only become extensive during the present generation.

Synthesis

Taking these various observations together, a tentative record of the rainfall fluctuations in the region can be constructed. Since much of the evidence is derived from valleys of rivers that drain the uplands, it may be argued that this reflects rainfall conditions above the

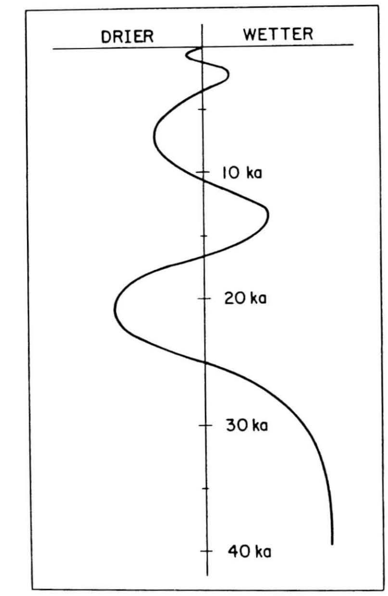

Fig.3. Tentative model of changes in precipitation and run-off in the Namib Desert and hinterland since 40,000 yr B.P.

escarpment. There is, however, no reason to expect that the general atmospheric circulation changed fundamentally during the period under consideration, so that precipitation changes in the inland would also be reflected in the desert. In addition, the observations regarding cut and fill in the main valleys are often paralleled in the side valleys which carry only local run-off. The generalized reconstruction of climatic change in terms of 'wetter' and 'drier' is shown in Fig.3. At present this curve is to be considered a working hypothesis only and, as investigations in the region proceed, it will undoubtedly need refinement or revision.

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Appendix

Radiocarbon dates (measured ages) of samples mentioned in the text

Pta-1493	Kuiseb Homeb, 8a, congl., S bank top	29,400 ± 520
Pta-2355	Kuiseb Homeb, 8b, congl., S bank top	28,900 ± 500
Pta-2329	Kuiseb Homeb, 8c, congl., S bank −14 m fr. 1	34,500 ± 1000
Pta-2330	fr. 2	35,600 ± 1500
Pta-2655	Kuiseb Qhormeb, 9, congl., N bank top fr. 1	29,100 ± 460
Pta-2656	fr. 2	38,200 ± 2200
Pta-2653	Kuiseb Qhormeb, 10, congl., N bank base	47,800 ± 4300
Pta-4521	Kuiseb Gr Hudaob, tufa, top	10,870 ± 90
Pta-4593	Kuiseb Gr Hudaob, tufa, −1 m	35,000 ± 880
Pta-4597	Kuiseb Gr Hudaob, tufa, tip of tongue	31,100 ± 680
Pta-4515	Kuiseb Nata Gamtes, tufa, tip	15,830 ± 120
Pta-3634	Kuiseb, Gobabeb, kindls 2nd terr	5300 ± 50
Pta-3628	Kuiseb, Gobabeb, kindls 1st terr	5870 ± 80
Pta-3823	Kuiseb, Gobabeb, crust −1 m	6710 ± 100
Pta-3833	Kuiseb, Gobabeb, crust −2 m	9340 ± 60
Pta-3647	Kuiseb Natab, crust, +7 m	5200 ± 70
Pta-3642	Kuiseb Natab, crust, +6 m	6840 ± 70
Pta-3442	Hoarusib Clay Castles, V4, rootcasts, high	18,890 ± 200
Pta-3466	Hoarusib Clay Castles, V7, crust, top	30,700 ± 1200
Pta-3537	Hoarusib Clay Castles, V6, snails +15 m	33,400 ± 1400
Pta-4122	Hoarusib Clay Castles, 12iii, crust	21,400 ± 200
Pta-4105	Hoarusib Clay Castles, 12i, kindl	42,600 ± 2300
Pta-3549	Hoarusib Downstream, L9, nodule	29,600 ± 1100
Pta-3543	Hoarusib Downstream, L9, calc silt	34,700 ± 1000
Pta-3548	Hoarusib Downstream, L9, snails	39,200 ± 1900
Pta-3490	Hoarusib Leyland's drift, L13, termite nest	16,020 ± 160
Pta-3815	Hoarusib Leyland's drift, L12, snails	31,200 ± 1900
Pta-4301	Hoarusib R Mouth, sea shell, beach	5250 ± 70
Pta-3866	Hoarusib R Mouth, crust, low	5230 ± 70
Pta-3868	Hoarusib R Mouth, kindl, top	4060 ± 70

Pta-3870	Hoarusib R Mouth, calc. silt, −3 m	1540±50
Pta-3447	Hoarusib Young Terr, V2, plant frag. −2 m	890±20
Pta-3841	Hoarusib Young Terr, V2, root −2 m	860±50
Pta-3876	Hoarusib Young Terr, 39, branch −1.5 m	720±35
Pta-8377	Hoarusib Young Terr, log	1120±50
Pta-3515	Hoarusib Young Terr, L7, charcoal	900±50
Pta-4535	Hoarusib Young Terr, wood	880±40
Pta-3933	Mudorib High Terr, 9/vi, crust −465 cm	32,100±770
Pta-4116	Mudorib High Terr, 9/v, crust −580 cm	35,600±1200
Pta-4112	Mudorib High Terr, 9/iii, crust −696 cm	35,300±770
Pta-4110	Mudorib High Terr, 9/i, crust −777 cm	36,900±1400
Pta-3890	Hoanib Young Terr, 5, log	1120±50
Pta-3880	Hoanib Flood plain, buried tree	350±40
Pta-3912	Hoanib Oasis, calc. silt	4890±60
Pta-4538	Khumib low silt, log	310±40
Pta-3474	Khumib Sarusas W Waterhole, reedbed +10 m	11,900±110
Pta-3479	Khumib Sarusas W Waterhole, reedbed +8 m	11,380±110
Pta-3495	Munutum Okau, calc. reedbed, fr. 1	12,730±120
Pta-3511	fr. 2	12,830±160
Pta-3531	Cape Fria, Karlova's camp, L17, calc. reedbed	12,930±120
Pta-3260	Narabeb N, calcrete −30 cm	11,470±80
Pta-3261	Tsondab flats, calcrete −15 cm	12,110±100
Pta-3262	Gobabeb plains, calcrete, top	10,000±80
Pta-3184	Koichab Pan, calc. reedbed, fr. 1	23,800±340
Pta-3185	fr. 2	23,300±330
Pta-3528	Hoanib Oasis, calc. reedbed	24,600±350
Pta-3516	Khowaribschlucht, calc. reedbed	25,900±400
Pta-3186	Möwe Bay, camp, calc. reedbed, fr. 1	30,000±620
Pta-3187	fr. 2	29,300±560

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