Climate change over the past 135,000 years in the Namib Desert (Namibia) derived from proxy data

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ABSTRACT

The study of natural climate change over glacial-interglacial timescales improves the understanding of the mechanics of climate. But this approach is limited by the number and distribution of well-dated and reliable palaeoenvironmental records. A much discussed question is the conflicting evidence for precipitation changes during the last glacial maximum in the Namib Desert, and the apparent shift of the zones of cyclonic winter rain and tropical summer rain in southern Africa. Here I present new data from the Namib Desert and from the continental interior of southern Africa to reconstruct precipitation changes in the hyper-arid coastal Namib Desert for the past 135,000 years. A re-evaluation of the palaeoenvironmental archives indicate that the hyper-arid Namib Desert experienced no significant changes in precipitation during the late Quaternary. One of the most important terrestrial records in the arid Namib Desert is a sequence of cave sinter in the Rössing Cave. The preliminary data from the speleothem indicate hyper-arid conditions in the coastal Namib Desert. These results agree with the palaeoclimatic interpretation of other desert sediments and with the results from AGCM (atmospheric general circulation model) experiments.

INTRODUCTION

Coastal deserts occur along the western shores of most continents. Some of these deserts are hyper-arid while others are semi-arid. In recent years, interdisciplinary research effort has focused on the age and origin of these deserts and their Quaternary climatic changes. The Namib Desert in south-western Africa with a length of about 1400 km and a width varying between 40 and

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120 km, is characterised by a climate that has been predominantly arid for approximately 40 million years (Kaiser, 1926; van Zinderen Bakker, 1975, 1984a; LEG 113 shipboard scientific members, 1987; Ward & Corbett, 1990; Partridge, 1993). Palaeoclimatic evidence from semi-consolidated (stiff) muds from the Namibian continental margin suggests that the northern and southern parts of the interior have become progressively drier since Miocene time. This result is based on an increase in the concentration of illite over time (Bremner & Willis, 1993). Pollen assemblages from marine cores off the coast document arid climatic conditions along the coast ever since Pliocene times. Different authors have discussed recently whether more humid phases occurred in the Namib Desert and surrounding areas during the late Quaternary (van Zinderen Bakker, 1984b; Heine, 1992; Rust, 1989; Teller et al., 1990; Brook et al., 1996).

Whether the central Namib Desert was affected by cyclonic winter rains during the last glacial maximum (Fig. 1) is a central issue in palaeoclimatic research. The hypothesis that the central and southern Namib Desert during the last glacial maximum experienced precipitation changes similar to many arid regions, rests primarily on the reconstruction of past sea surface temperatures based on faunal abundances and isotopic compositions (Schneider, 1995; Morley & Hays, 1979; Wefer, 1990), on pollen studies from South Africa (Scott, 1989, 1995; Scott et al., 1995), on sedimentological and palaeohydrological evidence from late Quaternary lake deposits in the northern Namib Sand Sea (Teller et al., 1990), and on the palaeoclimatic interpretation of fluvial land forms along the dry river beds of the Namib Desert (Vogel, 1982; Rust, 1989). Furthermore, from the interior of southern Africa, precipitation changes during the last glacial maximum are known (Thomas & Shaw, 1991; Buch et al., 1992; Tyson, 1986; Deacon & Lancaster, 1988). These studies indicate changes of available moisture between the last glacial maximum and the Holocene. Recent support for these results comes from the flash-flood sediments and their ichnofacies at the late Pleistocene Homeb Silt sections (Smith et al., 1993) and from cave sinter in Namibia (Brook et al., 1996). On the other hand, speleothem palaeoclimate records from the hyper-arid central Namib Desert suggest that this part of the Namib Desert was arid throughout the last glacial cycle. No speleothem formation could be observed during the last 25,000 ^{14}C yr BP (according to ^{14}C ages) or during the last 60,000 yr BP (according to [230]Th/[234]U ages) (Heine, 1992, 1997). This observation suggests that since OIS 2 (oxygen isotope stage 2, last glacial maximum) precipitation changes did not occur in the coastal zone of the central Namib Desert.

Here I present a brief summary and evaluation of continental palaeoprecipitation records from the Namib Desert, which include new palaeoclimatic proxy records and could reconcile the different views about the late Quaternary climatic fluctuations in the central Namib Desert. My palaeoecological interpretation of sediments and landforms together with numerous ^{14}C dates
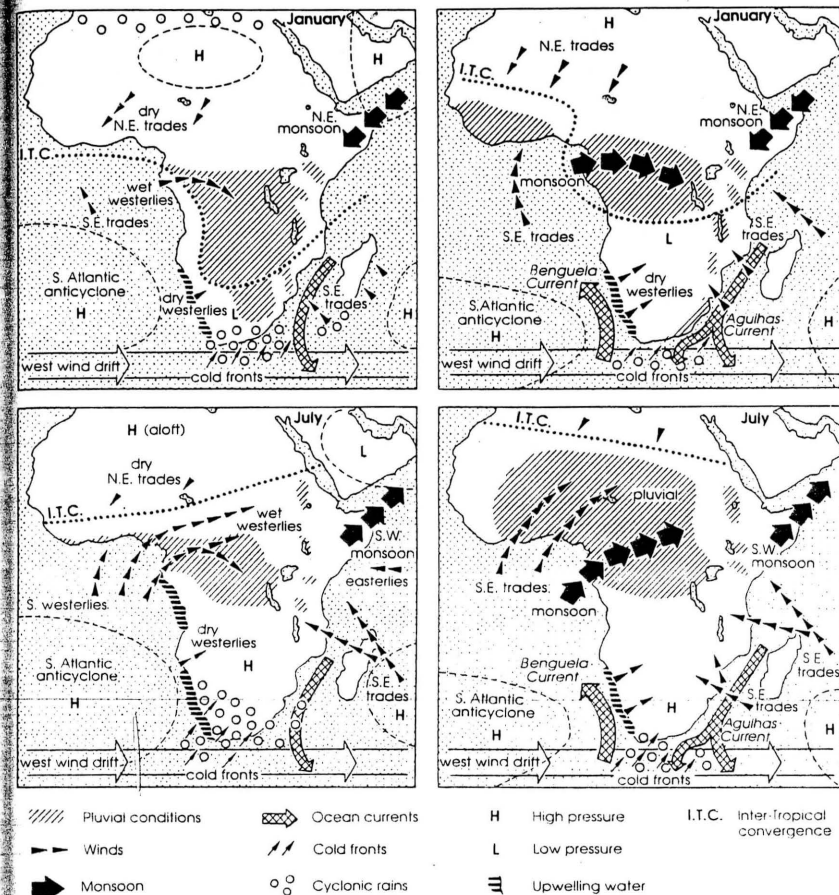

Figure 1. General model of circulation types on the African continent. Left: Glacial climatic trend, right: Interglacial climatic trend. After Shaw, 1985.

from calcretes, fossil soil horizons, speleothems etc. indicates that variations in rainfall did not occur in the hyper-arid coastal areas of the central Namib Desert during the late Quaternary. The available data suggests that during the last glacial cycle (OIS 4-1) at least this part of the Namib Desert was not affected by more rainfall as at present.

Well-dated and reliable palaeoenvironmental records with respect to temperature changes are not available from the Namib Desert. No palaeotemperature records exist to this date. Whether a low-latitude glacial cooling of

5°C (= estimates of the SST changes between the LGM and the Holocene, see Colonna et al., 1996; Guilderson et al., 1994) or more than 5°C in the southern hemisphere as suggested by Miller et al. (1997) affected the Namib Desert, may be resolved by proxy temperature series based on oxygen isotope analyses of the speleothems from the Rössing Cave. Noble gas temperature as a function of corrected radiocarbon age derived from the Stampriet aquifer (24,4°S, 18,4°E, Namibian Highland) indicate that the mean annual temperature in Namibia was about 5.3°C lower during the last glacial maximum as compared to today (Stute & Talma, 1997). Atlantic SST estimates off the Namibian coast (20-28°S), are 3-5°C cooler than today for the LGM (Morley & Hays, 1979).

Little is known about shifts of the southern and northern margins of the Namib Desert during the last 135,000 years. East of the Namib Desert (area of the Great Escarpment), sediment and soil sequences document late Quaternary moisture fluctuations that become increasingly accentuated towards north-east and east. More humid phases compared to today's climatic conditions occur >25,000 to 19,000 ^{14}C yr BP ago and about 10,000 to 8500 ^{14}C yr BP (according to soil formation), while lake sediments (lake marls) from Bullsport document wetter conditions after ca. 19,000 ^{14}C yr BP (Heine, 1993). The erosion of the well-dated Homeb Silts after ca. 19,000 ^{14}C yr BP suggests that higher rainfall occurred in the east of the Namib Desert. Wetter conditions in the Kalahari region have been postulated by Shaw & Thomas (1996). By applying the OSL (optically stimulated luminescence) method to 44 samples collected from the fossilised dunefields of western Zambia and the Caprivi Strip (northern Namibia) four periods of dune building (= aridity) between c. 35,000-45,000, 20,000-30,000, 8000-13,000 and 3000-5000 OSL yr BP can be recognised (O'Connor, 1997). Speleothems from the northern Namibian Highlands indicate drier conditions compared with today around 26,000-24,000, 13,000-11,000 and 9000-7500 yr BP (Brook et al., 1996) and wetter conditions prior to ca. 15,000 ^{14}C yr BP (Geyh, 1995), respectively.

GEOCHRONOLOGICAL PROBLEMS

A summary of geochronological aspects of palaeohydrological and palaeoclimatological results from Namibia is presented by Geyh (1995). He concludes that during the last three decades the Hannover ^{14}C Laboratory has performed ^{14}C age determinations of mainly carbonate samples collected in Namibia and South Africa in cooperation with several German institutes in order to contribute to the efforts for the establishment of a reliable chronology of the palaeoclimate. Many methodical problems hampered the geochronological interpretation of the dates which may be related to the arid climate of this region. Many geochronologists and palaeoclimatologists have questioned most of

these dates (Geyh, 1995; Heine, 1992, 1995, 1997). Attempts to overcome the difficulties were not convincing (Geyh, 1995). Since 1980, complementary U/Th age determinations on carbonate samples have been carried out by the Hannover Laboratory. Other problems became obvious by comparing both ^{14}C and U/Th dates (Geyh, 1995). In connection with an applied hydrological survey of the central Namib Desert and adjacent areas in Namibia by the BGR (Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover), ^{14}C age determinations of groundwater samples have been elaborated since 1990. These data confirm and complement the large number of ^{14}C dates of groundwater determined by Vogel in Pretoria (Geyh, 1995). Yet, groundwater ages of the coastal Namib Desert necessarily do not represent the precipitation in the area of sampling because of the groundwater movement from the interior to the coast.

Geyh (1995) points out that under these circumstances it is not surprising that partly contrary palaeoclimatic concepts were developed. According to Geyh (1995) the palaeoclimatological and palaeohydrological information of the accessible dates from Namibia is not yet definite due to methodical reasons and the suitability of the dated material. In 1992 Heine (1992) presents a synopsis of all ^{14}C dates from Namibia and Botswana which shows that there were only three pre-Holocene ^{14}C dates from samples that are not from inorganic sediments: 1. Wood from the Homeb Silts in the Kuiseb valley of the central Namib Desert (Vogel, 1982), 2. Material from a fossil Ah soil horizon from the southwestern Kalahari (Heine, 1982), and 3. Peat from the Makgadikgadi Pan of the Kalahari (Thomas & Shaw, 1991). Until now, no new pre-Holocene ^{14}C dates other than from inorganic material (calcrete, molluscs, calcified reeds etc., groundwater included) have been processed from Namib samples. Therefore, the possibility of contamination of the ^{14}C samples cannot be excluded.

From the Namib Desert, thermoluminescence (TL) ages of cave sands and fluvial silts have been reported by Heine (1992) and Eitel (1994, 1995). In the first case the dates show that the cave sands were blown into the cave before 64,000 and 87,000 TL yr BP (Heine, 1992); in the second case the TL ages confirm the ^{14}C dates of the Kuiseb Silt accumulation during OIS 2 (Eitel, 1994, 1995). L. Scheepers (personal communication 16.09.1996) gathered material from different terraces of the Uniab delta at the Skeleton Coast for TL age determination. The dates give minimum ages of the Uniab delta terraces that document precipitation conditions in the upper reaches of the Uniab catchment and/or of eustatic sea level changes and therefore do not represent climatic changes in the coastal Namib Desert.

U/Th age determinations of speleothems from the Namib Desert (Heine, 1988, 1991, 1992, 1997; Geyh, 1995) do not agree with ^{14}C dates. This problem is discussed in the section 'Caves and Speleothems' (see below).
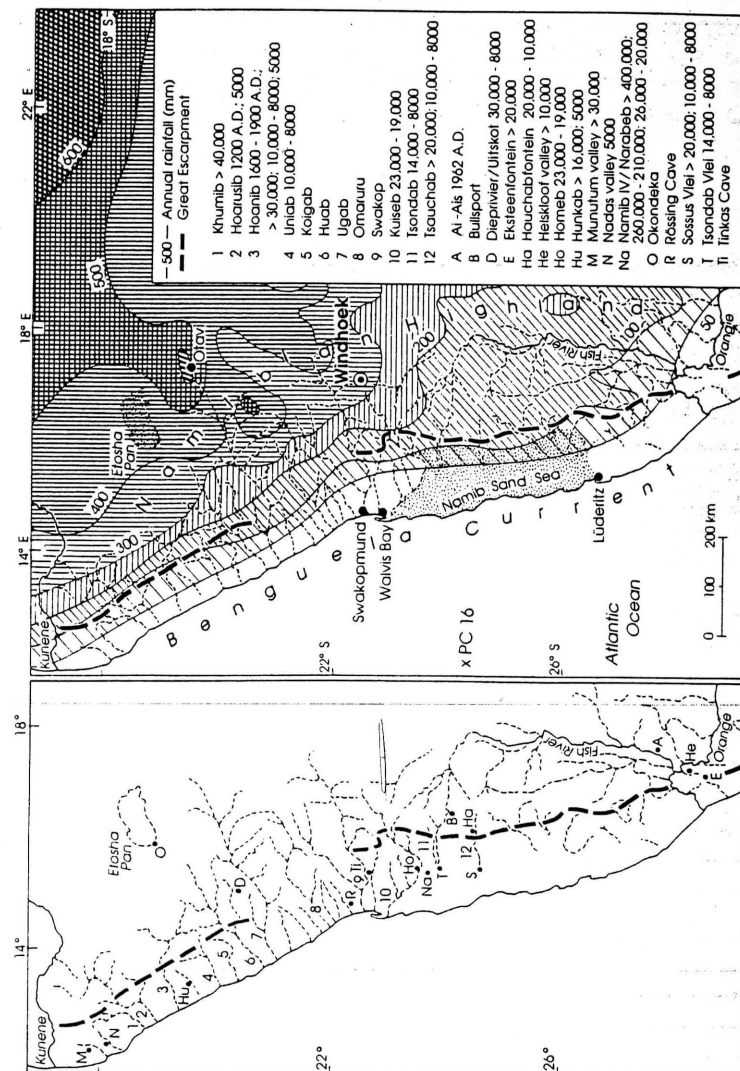
Figure 2. The Namib Desert (= area with < 100 mm annual rainfall). Ephemeral rivers and sites mentioned in the text. The age of silty fluvial sediments is given in ^{14}C yr BP and calender years AD.

FLUVIAL DEPOSITS

In the Namib Desert (Fig. 2), next to aeolian dust that is winnowed from the desert area, rivers are the main agents that transport the sediments from the inland toward the coast. Some rivers drain into the Atlantic, while others end in pans or vleis, where these sediments are deposited in terrestrial sequences or transported further to the continental shelf and Atlantic deep-sea basins to produce deep-water sediments. On the other hand, not all the sediment made available by the weathering processes on land is ultimately carried to the Atlantic or pans (vleis). Part of it also is deposited in the valleys under the influence of fluvial processes (Reineck & Singh, 1980). Rivers in the desert environment are ephemeral streams; they are dry most of the time except after heavy rains have fallen in their catchments. Twelve major ephemeral rivers flow through western and north-western Namibia and cross or reach the Namib Desert (Fig. 2). A number of smaller rivers originate in the arid coastlands and desert (Jacobson et al., 1995). In South Africa, the Orange River as well as a number of smaller ephemeral rivers flows through the Namib Desert.

The general characteristics of ephemeral rivers and fluvial processes of the Namib Desert have been discussed briefly (Heine, 1987); several fluvial sequences of late Quaternary age are described, explained, and interpreted palaeoclimatically. Here I summarise earlier results and add some new observations.

At Eksteenfontein in the arid western desert region of the Richtersveld (Fig. 2), stratified layers of sand, silty sand, and silt about 3.5 m thick document more humid conditions before the formation of the calcrete horizon and the slope deposits that are found on top of the sequence (Heine, 1993). According to ^{14}C ages of the section, the deposition of the pollen-bearing layers occurred between the late glacial and ca. 8000 ^{14}C yr BP (Scott et al., 1995), but the geomorphologic and pedologic evidence (calcrete and slope deposits above the sequence) in combination with an age of 19,400 ^{14}C yr BP for the calcrete horizon and our understanding of calcrete development in Namibia (Blümel & Eitel, 1994) suggests a much older age for the sediments (Heine, 1993).

At the confluence of the Orange River and the ephemeral river in the Helskloof valley, widespread silts were accumulated under arid conditions by back-flooding of the Orange River into embayments and tributary mouths during the late Pleistocene or early Holocene (Heine, 1987). During the last 5000 ^{14}C yr BP, slack-water sediments up to 14 m thick occurred as infills of back-flooded tributaries of the bedrock-controlled lower Orange valley (Zawada, 1995). Similar silty sediments were deposited by at least two different accumulation phases in the lower Fish River valley south of Ai-Ais. Both sediment sequences are interpreted as fluvial sediments deposited during flash-flood events by rapid accumulation from eddying currents as the flood-

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waters inundated the side valleys and creeks of the Fish River canyon. Clay mineral assemblages show variations in the illite/chlorite ratio and thus document the influence of different catchments (Heine, 1987). The youngest silt sequence was deposited by the A.D. 1962/63 floods of the Fish River.

Tsauchab and Tsondab Rivers drain a semiarid region in the east of the desert, ending in large vleis (pans) in the Namib Sand Sea (Plates 1 and 2). Accumulation of alternating water- and wind-laid sediments took place in the vleis during the late Quaternary, when fluvial silts were deposited mainly before 20,000 ^{14}C yr BP and after 10,000 ^{14}C yr BP (till 8500 ^{14}C yr BP) (Lancaster, 1984; Heine, 1987, 1993, 1995). Carbonate from silty deposits at Tsondab Vlei is dated to between 8600 and 14,000 ^{14}C yr BP (Vogel & Visser, 1981; Lancaster, 1984).

The most thoroughly studied of the ephemeral Namib rivers, the Kuiseb, originates in the Namibian Highlands and flows through the desert (for further references see Heine, 1985, 1995; Smith et al., 1993; Eitel, 1994). Palaeoclimatic information of late Pleistocene age comes from the Homeb Silt Formation (Vogel, 1982; Heine, 1995, 1997). Near Homeb, in the rock-walled canyon of the Kuiseb, relics of alluvial terraces are preserved (Plate 3). The sediments form isolated outcrops on the rock walls of tributary valleys. The age of the Homeb Silt Formation is dated by ^{14}C to 23,000-19,000 ^{14}C yr BP (Vogel, 1982) and by TL to between 18,300 ± 3400 BP (near the top) and 17,400 ± 3800 yr BP (near the base) (Eitel, 1994). Smith et al. (1993) investigated the sequence in detail. Soon after deposition, the sediment was colonised by burrowing organisms (mostly arthropods) that produced a *Taenidium* ichnofacies; after the floodwaters had drained, the silts were colonised by grasses and terrestrial arthropods (ants and termites), resulting in an overprint of *Termitichnus* ichnofacies with associated pelletal chambers. Although there seems to be little doubt about the observations by Smith et al., (1993) that the Homeb Silt Formation proves semi-arid rather than hyper-arid climatic conditions, some fundamental questions arise with respect to the origin of the Homeb silts. The Homeb silts probably were deposited as flash-flood fluvial sediments next to the main channel flow in overbank areas (mainly in tributary valleys). Similar accumulation processes occurred during the A.D. 1962/63 floods in the lower Fish River canyon (Heine, 1987). Floods travelling through the ephemeral rivers of the Namib Desert transport not only water and sandy silt but also massive amounts of soil, nutrients, organic matter, and seeds (Jacobson et al., 1995). Thus the structure of the ephemeral river ecosystems is influenced by the floods, producing a habitat or forming a refuge for a diverse array of organisms. The fact that the Homeb silts are not intercalated with slope debris at the rock walls (Hövermann, 1978; Heine, 1985) indicates hyper-arid climate conditions without major erosion and denudation of the gramadulla relief during the period of the Homeb silt accumulation. The sequence itself shows more rainfall in the upper catchment of the Kuiseb during a period of several thousand years around 20,000 ^{14}C yr BP.

In the upper parts of the Huab catchment, Eitel (1994, 1995) and Eitel & Zöller (1995) investigated fine sediments deposited by fluvial processes along small ephemeral rivers (Plate 4, Fig. 3). Structure, petrographic composition, and ages of this sequence of eroded and redeposited calcretes and soils in the basin of Farm Dieprivier and Farm Uitskot show phases of deposition and weathering. Age determinations by TL, ^{14}C, and U/Th differ widely from each other. Geyh (1995) mentioned that the TL dates represent the ages of transport and deposition of the sediments; the ^{14}C ages may reflect an influence by recrystallisation of carbonate, whereas the U/Th ages may document the period of the calcrete formation and their inverse ages show that the younger calcretes were eroded, transported and accumulated first and the older calcretes thereafter. The section shows that dating of ephemeral river silts is problematical, if only a few data produced by a single method (e.g. [14]C ages of calcareous material) are available. Palaeoclimatic information from these sequences are very limited and require further investigations (Eitel, 1995).

The fluvial silt sequences of the ephemeral rivers of the northern Namib Desert (Plates 5 and 6) are described by Rust (1987, 1989a, 1989b, 1994, 1995), Rust & Vogel (1988), and Vogel & Rust (1987, 1990). The formation
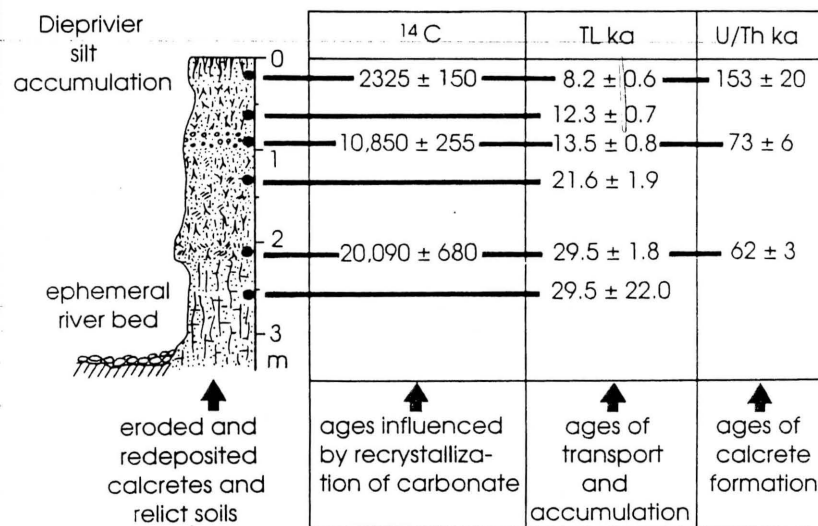

Figure 3. The Dieprivier and Uitskot sections with ^{14}C, TL, and U/Th ages (after Eitel & Zöller, 1995; Geyh, 1995).

of fluvial silt terraces occurred before 35,000 and 30,000 ^{14}C yr BP (Munutum, Khumib, Hoanib, Hoarusib), before 16,000 ^{14}C yr BP (Hunkab), and during the Holocene between 10,000 and 8000 ^{14}C yr BP (Unjab, Hoanib), at about 5000 ^{14}C yr BP (Nadas, Hoarusib, Hoanib, Hunkab), and during the Litle Ice Ace (Hoarusib, Hoanib), according to conventional ^{14}C ages of pedogenic calcretes, calcareous silts, calcareous concretions (kindel), and vegetation remnants. The results of Vogel & Rust (1987) confirm also that considerable floods of the Hoanib have passed through the dunefield during the last centuries to spill into the Atlantic.

From all evidence of the fluvial silt sequences along the ephemeral rivers of the Namib Desert I conclude that fluvial accumulation and erosion along the Namib Desert river valleys represent the processes and climatic situation of the headwaters (area of the Great Escarpment, Namibian Highland, semiarid eastern parts of the desert) and not the hyper-arid Namib Desert near the Atlantic coast. The terraces along the middle parts of the Namib rivers have been interpreted to reflect climatic fluctuations of the Namib Desert (Rust, 1989a, 1989b, 1994), but this view is questioned by the above interpretations. Furthermore, dating of fluvial and vlei sediments is problematical, as is shown by the Dieprivier section as well as by the Homeb Silt Formation. In addition, mighty silt accumulation occurred not only during late Pleistocene times but also during the recent centuries (Hoanib, Hoarusib). This shows that silt accumulation is a characteristic process in the arid Namib river valleys and no indicator for climate change in the hyper-arid Namib Desert itself (Heine, 1987).

LACUSTRINE DEPOSITS

In the Namib Sand Sea (Plates 1 and 2), the extent and significance of interdune lacustrine deposits in ancient aeolian sedimentary environments has been recognised by many authors (Lancaster, 1984; Lancaster & Teller, 1988; Teller & Lancaster, 1986; Selby et al., 1979; Teller et al., 1988, 1990; Teller, this volume; Heine, 1991). Outcrops of calcareous mudstones, sandstones, and of sandy limestones commonly occur in shallow depressions and appear to have been deposited in shallow ephemeral or seasonal water bodies (Lancaster & Teller, 1988). These sediments accumulated during different periods of the Quaternary. Fossils of *Elephas recki* (Shackley 1980) associated with Acheulean stone artefacts point to a Middle Pleistocene age (400,000-700,000 yr BP), U/Th dates to an age of 210,000-260,000 yr BP (Selby et al., 1979), and ^{14}C dates to an age between 20,000 and 26,000 ^{14}C yr BP (Teller & Lancaster, 1986) for the Namib IV and Narabeb sites in the northern sand sea. In other interdune lacustrine carbonates and molluscs, dates also cluster between 20,000 and 26,000 ^{14}C yr BP (Vogel & Visser, 1981; Teller & Lancaster,

1986; Teller et al., 1990; see also Heine, 1991). The radiocarbon dates are at variance to the geomorphological, sedimentological, and palaeontological evidence as well as with the results of the U/Th method (Heine, 1991). Teller et al. (1988, 1990) and Teller (1997, this volume) argue that the lacustrine deposits might show influences from the interior by groundwater seepage, by ponding at the end point of the Tsondab River, by flooding into the interdune corridors from the Kuiseb River valley or by increased rainfall in the headwaters. The detailed study of the Tsondab Valley and Tsondab Vlei sediments and their palaeoclimatic interpretation suggest (Lancaster, 1984) that all observed eight late Cenozoic periods with varying degree of fluvial activity are associated with an arid or semi-arid climate. The lacustrine deposits of the Namib Desert do not give a convincing evidence for major fluctuations in precipitation during the late Quaternary.

MARINE CORES

From ocean sediment suites and their pollen assemblages along the south-west African coast (Holes 532 and 530A, Leg 75, DSDP), van Zinderen Bakker (1984a, 1984c) concludes that the climate of the northern Namib Desert must have been hyper-arid during the Plio-Pleistocene (see also Scott, 1995). Reviewing the published evidence, van Zinderen Bakker (1984a, 1984b) concluded that no agreement had been reached on whether cyclonic winter rains occurred in the southern Namib desert, but he discerned a trend toward postulating dry conditions for 18,000 ^{14}C yr BP. Diester-Haass et al. (1988) investigated the core PC 16 from the south-west African continental slope (24°04'17"S, 12°39'93"E). During OIS 2 and 3, an increase in the local supply of terrigenous matter was observed with an increase in grain size. The occurrence of wood fibres in sediments older than 27,000 yr BP suggests a more humid climate with denser vegetation. The transport mechanisms of these plant fragments could be either aeolian or fluvial or both (Diester-Haass et al., 1988). These observations point to greater humidity during OIS 3, but the organic fragments can originate from the eastern parts of the desert or even from the highland and these consequently do not provide an unequivocal evidence for a significant change in precipitation in the coastal central Namib Desert.

POLLEN EVIDENCE

In the Namib Desert, plant remains such as seeds or pollen grains are very scarce in sedimentary sequences. Therefore, the interpretation of Quaternary vegetational change cannot rely on direct evidence from polleniferous deposits. Only two pollen sections from the Namib Desert have been published (van
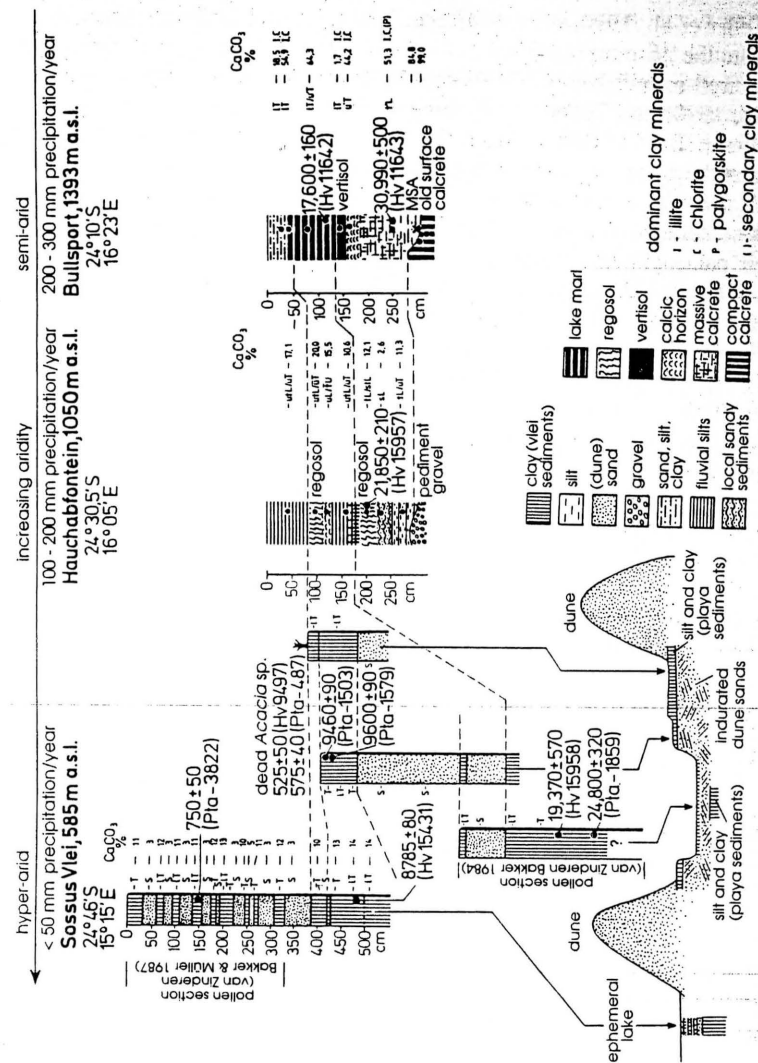
Figure 4. Stratigraphic correlations of selected sections between Sossus Vlei (Namib Sand Sea) and Bullsport (Namibian Highland) (after Heine, 1993).

Zinderen Bakker, 1984b; van Zinderen Bakker & Müller, 1987). The authors discuss the late Quaternary sediments occurring in the Sossus Vlei, the end-point of the Tsauchab River (Plate 1). The ephemeral river originates in the area of the Great Escarpment (Naukluft Mountains), flows through a deep narrow canyon carved into deposits of alluvial sediments, and ends amongst the dunes of the main Namib Sand Sea (Jacobson et al., 1995), where pans at different levels indicate a blocking of the Tsauchab by moving dunes. In the pans (Plate 2), sequences of alternating fluvial silt and aeolian sand layers are found (Heine, 1987, 1993). The pollen and ^{14}C data (van Zinderen Bakker, 1984b; van Zinderen Bakker & Müller, 1987) indicate that the northern part of the Namib Sand Sea did not receive significantly more rainfall over the last ca. 18,000 ^{14}C years, which contradicts suggestions of more than usual winter rainfall in the central Namib Desert and the Sand Sea (van Zinderen Bakker, 1976). However, the amount and annual distribution of precipitation in the area of the Great Escarpment, which is strongly influenced by the position of the South Atlantic anticyclone, remains unknown.

From Holocene pollen sections in Namibia east of the desert, Scott et al. (1991) suggest wetter climatic conditions in the Windhoek area between 7000 and 6000 ^{14}C yr BP and some minor climatic fluctuations thereafter.

SOILS

In the area between Sossus Vlei in the Namib Sand Sea in the west and Bullsport in the east of the Great Escarpment fossil soils of late Quaternary age point to climatic fluctuations (Heine, 1993, 1995). Selected sections (Fig. 4) present the stratigraphic correlations between paleosols and lacustrine sediments. Thick silt deposits of the Sossus Vlei (Plate 2) correspond to the regosols of the Hauchabfontein area and the vertisols of the Bullsport section. The lake deposits of the Bullsport section have ^{14}C dated to 17,600 yr BP and thus were deposited during the last glacial maximum (ca. 18,000-14,000 ^{14}C yr BP). At the same time at Hauchabfontein (eastern edge of the Namib Desert, Plate 1) silty layers were deposited by an ephemeral river with subsequent regosol development and at Sossus Vlei aeolian sands were blown into the pans. In the Namib Sand Sea the last glacial maximum seems to have been dominated by aeolian processes and there is no evidence for increasing moisture. At the beginning of the Holocene once more thick silt deposits were deposited in the Sossus Vlei pans. The ^{14}C ages date the period of older soil formation between >25,000 to ca. 19,000 yr BP and the younger one between about 17,000 and 8500 ^{14}C yr BP. The evidence from fossil soils indicates that the intensity of the observed climatic fluctuations increases from west (Namib Desert) to east (Namibian Highland).

The first comprehensive investigation of the wide-spread gypcretes of the central Namib Desert (Plate 7) show that the gypcretes are of pedogenic origin, that the formation of gypcretes is very slow, and that the gypcretes document hyper-arid conditions without any major humid phase during the last 100,000 yr BP, at least (Heine & Walter, 1996a, 1996b). The authors clearly document that gypsum appears to move from the surface down into the soil. The slow gypcrete development is supported by the findings of Eckardt (1996) that marine aerosols deposit the sulphur (and calcium, sodium, and other elements) at the desert surface, where rain water will gradually dissolve this material and move it deeper into the soil, producing gypsum as well as halite. These processes and deposits only can occur under a continuous arid climate and document the long aridity of the central Namib Desert.

CAVES AND SPELEOTHEMS

Despite continuous research for many decades, no long and detailed geomorphologic or palynologic records have been identified in the Namib desert. Long, datable sediment sequences may be present in the Rössing Cave, located approximately 30 km east of the Atlantic coast (north-east of Swakopmund). Calcite deposits formed in limestone caves have been identified as an excellent source of palaeoclimatic data (temperature, precipitation) for terrestrial environments (Gascoyne, 1992). The karst dynamic system is particularly sensitive to environmental change, permitting high resolution on a scale of centuries, decades, and, under certain conditions, annual seasons (Brook, 1995). Studies of stalagmites and other cave sinters from the Rössing Cave and the Tinkas Cave in the central Namib Desert have revealed new aspects on climatic change of the late Quaternary (Heine & Geyh, 1984; Heine, 1988, 1992, 1997).

The Rössing Cave has developed in interbedded marble, schist, and calcsilicate rock of the Damara Sequence (isotopic age 650-900 Ma). The marble tends to form a prominent continuous ridge. As this marble ridge is more resistant to denudation, it surmounts the Namib erosion surface by several metres to tens of metres. The speleothem formation depends on local precipitation since surface and/or groundwater influx from far away is excluded by the geomorphic setting of the marble ridges (Heine & Geyh, 1984). The cave itself must have developed under a comparatively humid climatic regime, probably before the late Miocene/early Pliocene calcrete formation on the Namib peneplain. From the cave, many stalagmite, stalagtite, flowstone, cave popcorn, and other samples were radiocarbon-dated. The resulting ages are all older than 25,000 ^{14}C yr BP. Compact speleothems are older than 35,000 ^{14}C yr BP. According to the ^{14}C dates, no sinter growth occurred after 25,000 ^{14}C yr BP (Heine, 1997; Geyh, 1995). Additionally, several speleothem samples were

dated by ^{230}Th/^{234}U. The results differ considerably from the ^{14}C dates. Furthermore, some TL age determinations from sands that were blown into the cave yield minimum ages of > 64,000 and >87,000 yr BP.

Hitherto, the interpretation of the dates from the cave speleothems is difficult because of methodological problems (Heine, 1992; Geyh, 1995). In order to achieve better age control and more palaeoclimatic information from the speleothems (Fig. 5), a new project based on AMS (accelerator mass spec-

Figure 5. Section of stalagmite from Rössing Cave, central Namib Desert. U/Th age determinations (in 1000 yr BP) have shown no major change in precipitation during the last 135,000 years.

trometry) ^{14}C and TIMS (thermal-ionisation mass spectrometry) U/Th dates has been initiated. Palaeomagnetism and X-ray analyses (radiographs) as well as XRD analyses and thin sections will contribute to a better understanding of the conditions during sinter growth. Furthermore, variations in ^{13}C and [18]O content of the calcite, in trace element concentrations, and in pollen assemblages should yield to synchronous palaeoclimatic information. In September 1996, several cores (diameter 62 mm) were gathered from the stalagmite that shows evidence for the youngest sinter growth in the cave. The stalagmite is about 100 cm long and is situated at the end of the cave where the relative humidity is relatively high and the air flow low. The cores were taken from the base, the central part, and the top of the stalagmite.

In addition to the information published by Heine (1997) and in earlier papers (Heine & Geyh, 1984; Heine, 1992; Geyh, 1995), thin sections from the cores document that the sinter growth was very slow and cone-like. The outer few centimetres of the stalagmite (4-8 cm, about 100 laminae) show very thin growth layers, often less than 0.3-0.1 mm in the outer 0.5 cm and slightly thicker laminae in the following 0.5 cm. The thickness of the layers increases abruptly 4-8 cm beneath the surface. Several erosional surfaces show that the sinter growth was interrupted and that dissolution occurred from time to time. The planned mass spectrometric dating will provide a record of the timing of growth commencement and cessation. According to the ^{230}Th/^{234}U dates processed so far from samples of the stalagmite, the outer 0.5 cm date to 121,000 ± 3000 yr BP and the following next 0.5 cm to 213,000 ± 9000 yr BP (Heine, 1997; Geyh, 1995). By extrapolating these dates, the pronounced hiatus (erosion surface) that separates the outer fine-layered part from the inner lighter and thicker calcite layers has an age of circa 800,000 yr BP. AMS ^{14}C ages of the outermost layer of the stalagmite yield ages of 15,704 ± 167 yr BP (16,800-16,475 cal yr BC, 1 sigma confidence; ERL-685) and 17,811 ± 132 yr BP (19,475-19,125 cal yr. BC, 1 sigma confidence; ERL-680).

The analyses of the core KOO 930 corroborate the antiquity of the stalagmite, the slow growth processes, and the late Quaternary aridity in the coastal central Namib Desert. On the other hand, these results confirm three major phases of sinter development that differ considerably from each other. The Tertiary phase with thick layers and sandy inclusions, the Middle Pleistocene phase (ca. 800,000-130,000 yr BP) with thin layers, and the youngest phase since about OIS 5 with extremely thin growth laminae. Thus, the progressing aridity is documented in the stalagmite laminae showing a drastic change in precipitation around 800,000 yr BP. This change seems to be related to a change in orbital forcing; prior to ca. 800,000 yr BP the glacial cycles were correlated to the obliquity (ca. 41,000 yr), thereafter to the eccentricity (ca. 100,000 yr). Since about 800,000 yr ago the great glaciations occurred on the earth. The central Namib Desert stalagmite reflects the transition from the 41,000 yr cycle-era to the 100,000 yr cycle-era. This transition seems to have
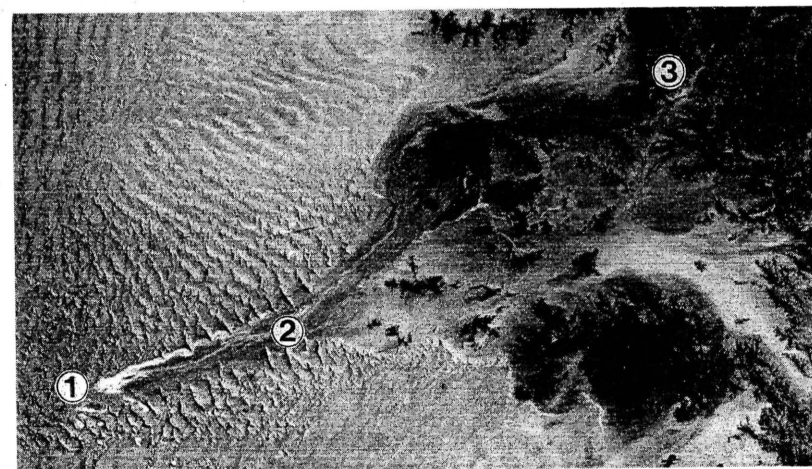

Plate 1. Satellite image of the eastern margin of the Namib with ephemeral rivers draining a semiarid region in the east of the desert, ending in large vleis (pans) in the Namib Sand Sea. (1) Sossus Vlei, (2) Tsauchab valley, (3) Hauchabfontein. See Figure 4. (Photo NASA).
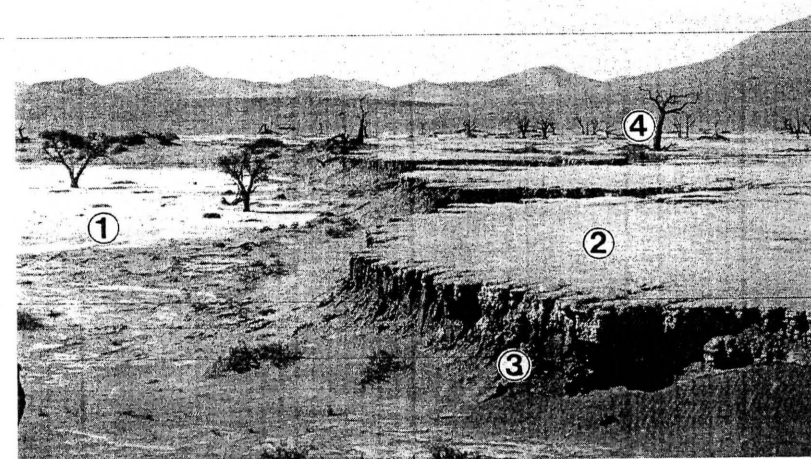

Plate 2. Sossus Vlei with late Quaternary silty lacustrine sediments (circa 20,000 ^{14}C yr BP) to the left, lower part (1), and early Holocene vlei silts (circa 9500 ^{14}C yr BP) (2) on top of late Quaternary capped sand dunes (3) in the right part of the picture. The dead Acacia trees (4) on the early Holocene silts died around 550 ^{14}C yr BP. See section Sossus Vlei of Figure 4. (Photo K. Heine 04.10.1978).
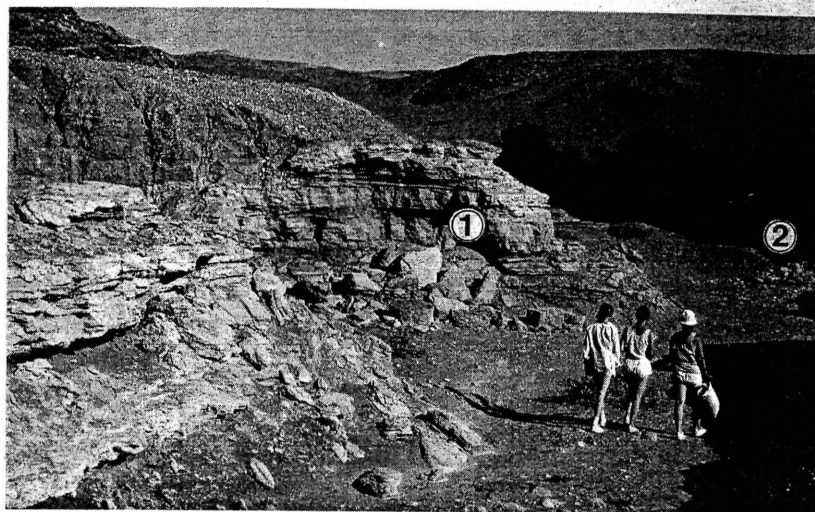
Plate 3. Homeb Silts (1) in the Kuiseb Valley (2). The silts accumulated between 23,000 and 19,000 ^{14}C yr BP, probably as flash-flood fluvial sediments next to the main channel flow in overbank areas. The Homeb silts document more rainfall in the upper catchment of the Kuiseb. (Photo K. Heine 31.07.1988).
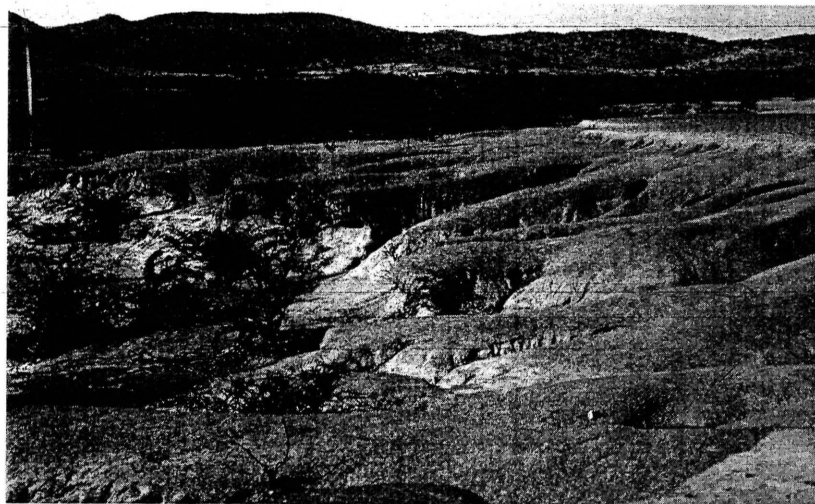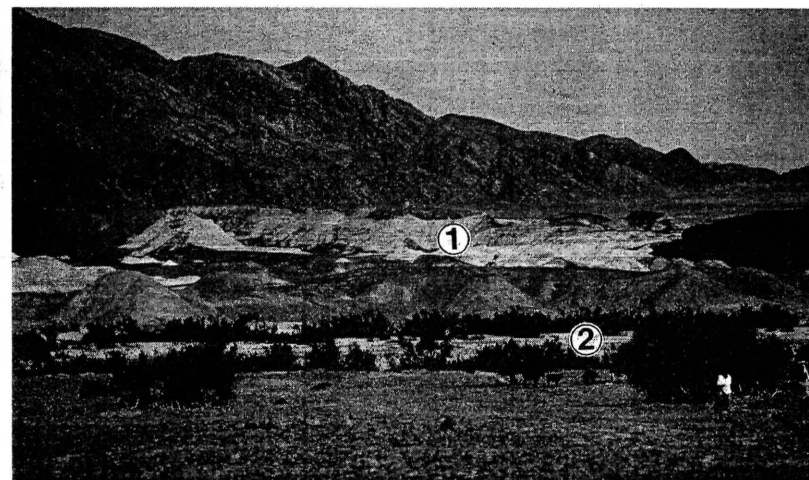

Plate 5. Hoarusib valley with Clay Castle Silts (1). The silts beyond the Hoarusib flood plain (2) were deposited before 40,000 ^{14}C yr BP. They indicate large floods coming from the areas east of the Great Escarpment. (Photo K. Heine 26.08.1996).

Plate 4. A sequence of eroded and redeposited calcretes and soils in the upper parts of the Huab catchment (near Farm Uitskot). See Figure 3 and text for further explanations. (Photo K. Heine 23.03.1993).
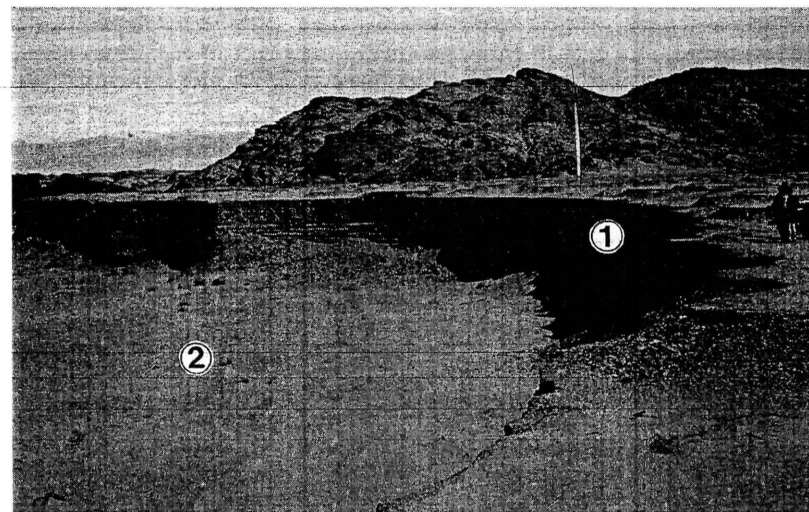
Plate 6. Hoanib valley with Amspoort Silts (1). These sediments accumulated during the Little Ice Age (1600-1900 AD). During the last two centuries, sedimentation was followed by erosion (2) of large parts of the silts. (Photo K. Heine 31.08.1996).
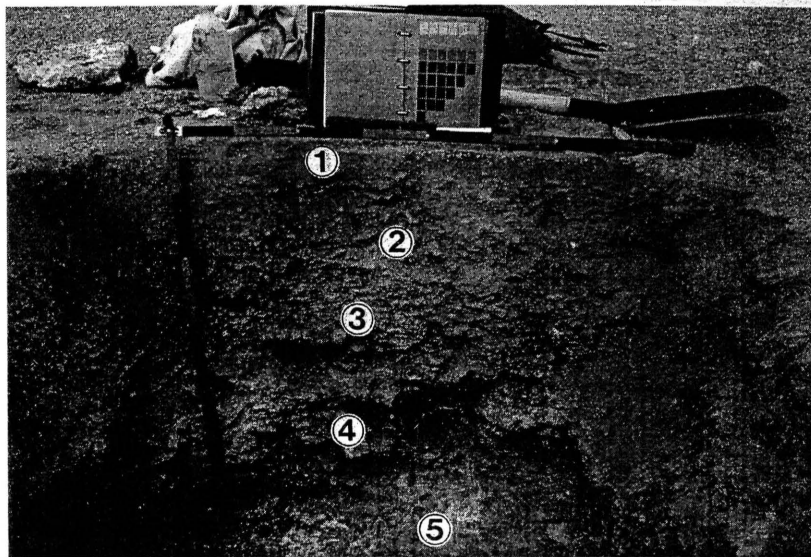
Plate 7. Gypcrete of the Namib Desert 3.5 km north of Gobabeb. The fully developed gypsum soil shows, from top to bottom, (1) a layer of eolian material, (2) a gypsum crust consisting of a gypsum-plugged matrix with stones and smaller debris floating in the gypsum matrix, (3) a gypsum crust mixed with weathered carbonate cementations, calcretes, and decomposed bedrock, (4) a horizon rich in $CaCO_3$ with gypsum minerals, and (5) calcrete. (Photo R. Walter 22.01.1993).
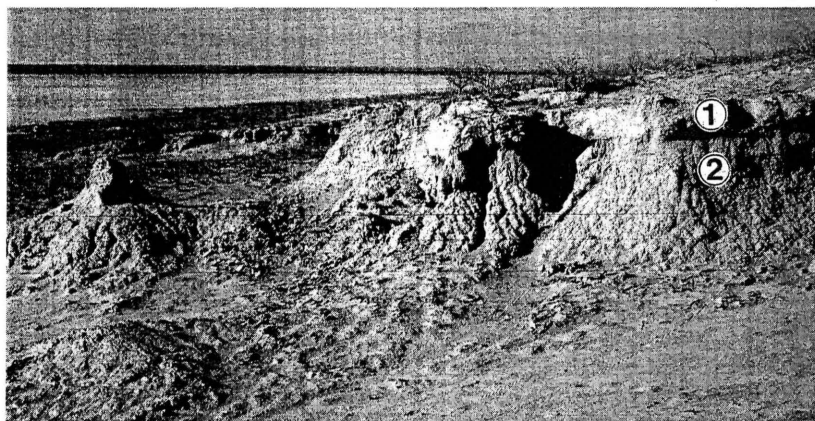

Plate 8. Etosha Pan, Logan's Island. Soil section with (1) eolian cover sediments (circa 35 cm thick) on top of (2) the Okondeka I paleosol (8000-5000 TL yr BP). (Photo K. Heine 14.10.1992).

been influenced the general climatic situation of the central Namib Desert and also may be found in the geomorphologic setting of the Kuiseb River valley (Heine, 1990a).

EVIDENCE FROM ADJACENT AREAS

During recent years many palaeoclimatic data from the Upper Pleistocene and Holocene have become available from adjacent areas to the Namib Desert in Namibia.

In 1988, a project was started (Heine, 1991) to clarify peculiarities of climatic change in northern Namibia, on the western shore of the Etosha Pan where a set of lunette dunes provide new opportunities for a chronostratigraphical differentiation of the late Quaternary and for a highly resolved reconstruction of environmental change (Heine, 1991; Buch, 1996). The geomorphological, sedimentological, and pedological observations from the Etosha region reveal a remarkable persistence of the environmental conditions during the Quaternary and especially during the last 140,000 yr BP (Heine, 1991, 1992; Buch, 1996; Buch & Zöller, 1992; Buch et al., 1992). A TL-calibrated pedostratigraphy of the lunette dunes (Fig. 6) indicate that since 140,000 yr BP only three periods of soil formation have occurred. The Okondeka III-lamella-soil is TL-dated between <140,000 yr BP and >70,000/75,000 yr BP, the Okondeka II-soil-complex to the period between 18,000 and 14,000 yr BP, and the Okondeka I-soil to 8000-5000 yr BP (Plate 8) (Buch et al., 1992). This lunette dune chronostratigraphy provides the first absolutely dated evidence of the intensity of late Quaternary climatic changes. The extremely weak soil development during different late Quaternary phases show that no major changes in precipitation occurred. Although the TL dating of the basal aeolian sand (Fig. 6) may be unreliable (because of methodical problems, see Heine, 1995), it is evident that the last ca. 130,000 yr BP were characterised by a semi-arid climate and that the Etosha Pan was not occupied by pluvial lakes as was postulated by Hövermann (1988) and Heine (1990b). Furthermore, it is shown that during OIS 5 precipitation was slightly higher, whereas OIS 4(?) and 3 were arid to semi-arid; the last glacial maximum between 18,000 and 14,000 yr BP experienced slightly wetter conditions, as did the Holocene between 8000 and 5000 yr BP. This ties in with other observations from the Namibian Highland.

For the entire Kalahari, Shaw & Thomas (1996) describe a wetter episode from 16,000 to 13,000 ^{14}C yr BP (according to radiocarbon-dated calcretes, sediments, molluscs, and wood samples). This is corroborated by detailed studies of fluvial sediments from the Auob, Nossop, and Molopo valleys in the southwestern Kalahari (Heine, 1981,1982, 1990b) and by findings for wetter periods around 17,000 to 15,000 ^{14}C yr BP in the Bullsport area (Heine, 1993;
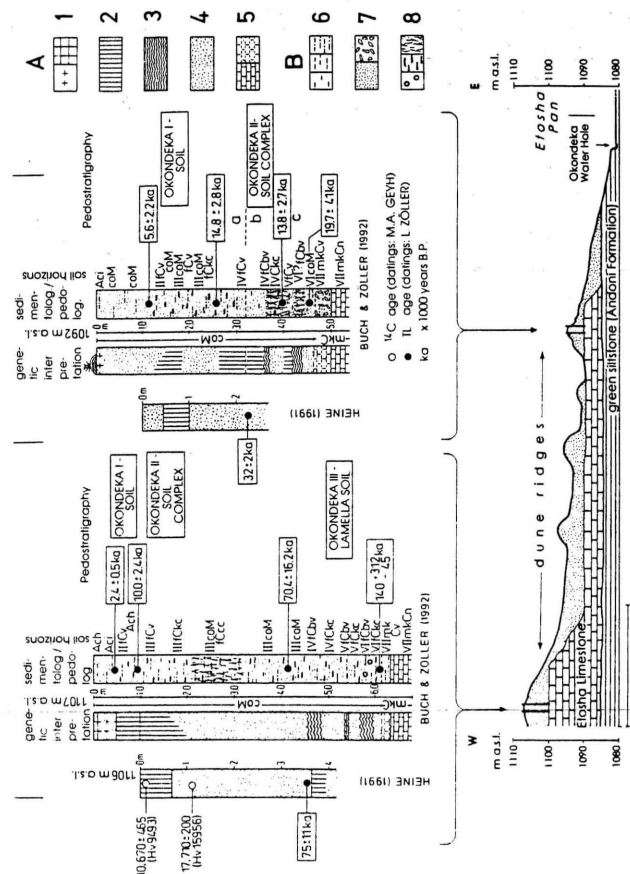
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Figure 6. Type-locality sections of the lunette dunes, Etosha area, Okondeka Water Hole (19°00'S, 15°50'E). Adapted from Buch (1996) and Buch et al. (1992), modified and supplemented. Sedimentologic and pedologic characteristics are described after AG Bodenkunde (1982). A) Genetic interpretations (1) initial organic enriched A-horizon/organic enriched A-horizon; (2) initial cambic horizon (Cv-horizon)/initial cambic horizon interspersed with fine roots; (3) initial cambic horizon, 'lamella-type', different intensities; (4) calcareous-rich to extremely calcareous aeolian sands; (5) 'Etosha Limestone' (unweathered)/'Etosha limeston' (weathered); B) Sedimen-tologic/pedologic descriptions (6) texture clay/silt/loam; (7) texture sand/rock splinters; (8) calcium carbonate concretions; round/irregular/calcium carbonate precipitation.

Fig. 4) as well as in the Mariental-Maltahöhe area (Hövermann, 1988), where lacustrine deposits indicate a pluvial phase. For the southwestern Kalahari Stokes et al. (1997) describe multiple episodes of aridity. Samples for optical dating (OSL = optically stimulated luminescence) from basal sediments within linear dunes consistently yielded ages exceeding 20,000 OSL yr BP, whereas analyses on sands from the body of dunes describing the main linear forms of the area generally indicate depositional ages in the range 10,000-20,000 OSL yr BP. In the Mega Kalahari, several significant arid events are apparent since the last interglacial period, with dune-building (arid) phases at ca. 95,000-115,000, 41,000-46,000, 20,000-26,000 and 9000-16,000 OSL yr BP (Stokes et al., 1997). The OSL ages from the southwestern Kalahari point to dune for-mation between 20,000 and 10,000 OSL yr BP (Stokes et al., 1997), whereas the ^{14}C dates (Shaw & Thomas, 1996) give evidence of wetter conditions. This discrepancy is solved by the evidence that aeolian and fluvial processes oc-curred at the same time during the last glacial maximum in the southwestern Kalahari (Heine, 1979, 1981, 1982, 1990b).

During the late Quaternary, especially for OIS 2 and 1, Brook et al. (1996) present a reconstruction of wet and dry periods in the southern African sum-mer rainfall zone by analysing speleothems and tufa. Dry periods occurred between 35,000 and 28,000 yr BP and between 11,000 and 8000 yr BP, wetter climatic conditions were identified during periods between 50,000 and 14,000 yr BP and – less accentuated – during the mid and late Holocene. Geyh (1995) reports stalagmite growth in a cave of the Otavi mountains (south of the Eto-sha Pan) until about 15,000 ^{14}C yr BP with a rapid decline in sinter accumula-tion between 15,000 and 7000 ^{14}C yr BP. This is interpreted as a climatic change to more aridity (Geyh, 1995).

Seasonal distribution of rainfall in southern Africa is an important aspect of palaeoclimatic reconstruction for the Namib Desert. It can be a major influ-ence on the relative proportion of C_3 and C_4 grasses in a region, since their relative distribution is essentially constrained by temperatures during the growing season; cool growing season favour C_3 grasses, whereas warm ones favour C_4 grasses. Dietary signals for animals with C_3- and C_4-based diets are maintained for millions of years in enamel. $^{13}C/^{12}C$ ratios in tooth enamel car-bonate of grazers from the northern Cape Province were used by Lee-Thorp & Beaumont (1995) to determine vegetation and rainfall seasonality shifts during the late Quaternary. The data show that the north-western Cape did not fall within the winter rainfall zone during the Upper Pleistocene. Instead, Lee-Thorp & Beaumont (1995) conclude that during the Upper Pleistocene periods of enhanced winter rainfall occurred within a predominantly summer rainfall regime (with more rain throughout the year, i.e. rainfall was less seasonal). Geomorpholgical and palaeontological evidence indicates that tropical sum-mer rains and cyclonic winter rains overlapped in the south-western Kalahari between 19,000 and 13,000 ^{14}C yr BP (Heine, 1982: Fig. 6, 1990b: Fig. 9).

This circulation pattern for southern Africa is also described by Leroux (1996), and a comparison of present-day locations of major divergences and convergences in the South Atlantic with their proposed LGM positions show a northward shift of only 1-3° of latitude at the LGM (Morley & Hays, 1979; see also Harrison, 1988).

Although it is difficult to reconstruct the precipitation changes prior to ca. 25,000 yr BP, because of the need for more reliable chronological data (TL, OSL, IRSL, U/Th, TIMS U/Th), some general inferences can be drawn: During the last ca. 130,000 yr BP, the intensity of precipitation fluctuations in Namibia increased from west (Namib Desert) to east and from south-west to north-east. The period of the last glacial maximum between ca. 18,000 and 14,000 ^{14}C yr BP was wetter than the periods before and after. This last glacial maximum wet phase was restricted to the summer rainfall zone in southern Africa and did not affect the coastal Namib Desert. The transition from the late glacial to the early Holocene was relatively arid. Wetter conditions started with the Holocene climatic optimum. This is in agreement with the results from the South African summer rainfall zone (Scott, 1989).

DISCUSSION

During the last 125,000 yr BP, the hyper-arid coastal zone of the Namib Desert experienced an arid climate without any precipitation changes greater than those comparable with the current desert climate. All morphological, sedimentological, pedological, and palaeontological evidence for late Quaternary fluctuations in precipitation can be explained by causes other than precipitation changes in the desert itself. The sensitivity of ephemeral rivers to climatic change is conditioned, in part, by the wide range in flood magnitude and by the erosional and depositional legacy of large events; very large floods, for instance, have recurrence intervals of the order of 10^3 years . Many observations from desert rivers suggest (Reid, 1994) that diagnosing climatic change from channel and sediment characteristics are prone to error. One problem is that each desert drainage basin is a unique permutation of all those factors that encourage or discourage runoff and sediment transfer (see Jacobson et al., 1995). Factors which act as regulators of change may be more important in one catchment than in another (Reid, 1994). The late Quaternary sequences of fluvial sediments from the Namib rivers clearly support this view.

The lacustrine deposits, most of which occur east of the hyper-arid coastal area of the desert, cannot contribute to the reconstruction of the late Quaternary changes in precipitation, either. They represent different sources of water in the desert (e.g. by penetration of rivers draining the highlands to the east, by seepage through the dunes, by flooding of interdune corridors from the river valleys, by groundwaters from the east).

The soils of the hyper-arid Namib Desert document arid conditions throughout late Quaternary times. So do the pollen sequences from the desert and from marine cores.

Cave sinters of the central Namib Desert seem to be most useful for palaeoenvironmental reconstructions. Although investigations continue and only preliminary results can be presented, the stalagmites document hyper-arid conditions by their morphology, cross-section, and growth rates for at least 125,000 yr BP. Conventional ^{14}C and U/Th ages cannot give exact rates of the deposition of the stalagmite because of the very fine laminae of calcite, but the data show that the stalagmite growth ceased before 25,000 ^{14}C yr BP.

The elucidation of the late Quaternary palaeoclimatic history of the Namib Desert has been a difficult and ambiguous task. Although many authors realised that the Namib Desert landforms and sediments have a palaeoclimatic significance, it is only with the discovery of the desert speleothems that the potential of cave calcites has been used as an archive of palaeoclimatic scientific data from the Namib Desert (Heine & Geyh, 1984). The speleothems shed new light on the precipitation changes during the last 125,000 yr BP. Evidence for aridity along the coastal Namib Desert comes from experiments with general circulation models (GCMs), too.

In most cases, general circulation modelling experiments are used to assess the impact of climate change (last glacial maximum conditions or enhanced greenhouse effect) on changes in annual or seasonal average surface temperatures and total rainfall amounts. However, in deserts many of the most important impacts will arise from changes in the magnitude and frequency of extreme events. In particular, changes in rainfall extremes have received very limited attention so far (Gordon et al., 1992).

A simulation of the atmosphere under ice age conditions (18,000 years ago) is presented by Lautenschlager (1991). The T21 AGCM (Atmospheric General Circulation Model) was used to simulate the 2 m-temperature, the 10 m-wind, and precipitation. The presentation is restricted to January and July averages (temperatures, winds, and precipitation) in order to demonstrate the changes in summer and winter during the glacial epoch. The model's response to the ice age boundary conditions is consistent with palaeoecological data on land and with AGCM experiments of other studies (Lautenschlager, 1991). Although the differences between the mean climate states of the T21 model atmosphere under glacial and modern boundary conditions were statistically significant, the basic structure of the simulated atmosphere circulation was not altered substantially (Lautenschlager, 1991) (Fig. 7). The results of the AGCM experiment are in close agreement with the observations from the Namib Desert. During the southern summer (January) a positive anomaly is shown with increasing values to the east and north-east in the Namibian area. Even during the southern winter (July) higher precipitation is suggested for the Kalahari region. According to the AGCM experiments the coastal Namib Desert did not
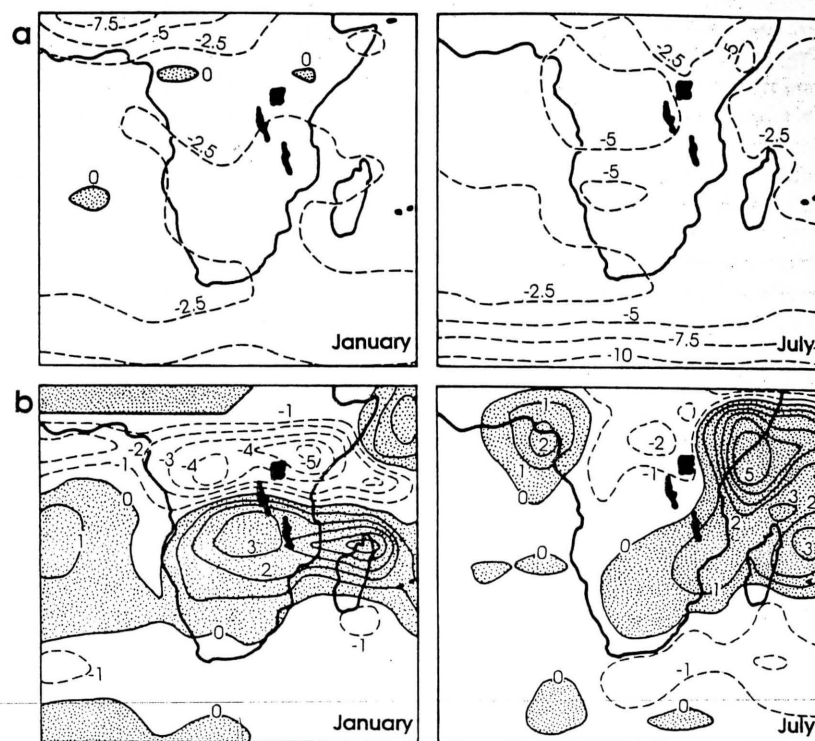
Figure 7. Simulation of the atmosphere under ice age conditions (18,000 ^{14}C yr BP) with the T21 Atmospheric General Circulation Model (= AGCM) (after Lautenschlager 1991). a) January and July mean temperature anomaly (ice age minus present) at 2 m. Contour interval 2.5°C. Positive anomalies are hatched. b) January and July mean precipitation anomaly (ice age minus present). Contour interval 1 mm/day. Positive anomalies are hatched.

experience any increase in precipitation during the last glacial maximum summer, nor during the last glacial maximum winter.

Both field evidence and modelling show that in the Namib Desert the late Quaternary changes in precipitation increased with increasing distance from the coast. In the Kalahari area the precipitation increase was significant. For the last glacial maximum, a shift of the Namib Desert margin to the west can be postulated. However, the coastal part of the Namib Desert was not influenced by more humidity. It remains unclear whether earlier OISs experienced similar changes. Partridge (1997) believes that the current east-west climatic gradient across southern Africa was established (at least temporarily) as far back as the early Cainozoic. The research on the stalagmite from the Rössing Cave may yield palaeoclimatic data spanning the last few 100,000 years.

The interpretation of the terrestrial proxy data from the Namib Desert suggests a prolonged period of aridity during the late Quaternary that was neither influenced by large climate changes nor the fast and abrupt climate variability recorded in Greenland ice cores, in long terrestrial sequences, or in marine sediment cores (Broecker, 1995). The late Quaternary climatic development of the Namib Desert reflects the surface oceanography in the South Atlantic Ocean which is characterised by a cyclonic gyre circulation including the northwest-directed Benguela Current, the eastward South Equatorial Counter Current, and the Angola Current which flows southward along the Angola Margin. Therefore, with regard to late Quaternary climatic change, the Namib Desert cannot be compared with the Sahara, Arabian, and Asian deserts.

ACKNOWLEDGEMENTS

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