Gypcretes of the central Namib Desert, Namibia

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ABSTRACT

The arid Namib Desert (ca. 15°S-29°S) stretches along the Atlantic coast of south-western Africa. The first comprehensive investigation of the widespread gypcretes of the central Namib Desert prove that: 1. The gypcretes are of pedogenic origin; fog precipitation carries sulphur from the Atlantic to the desert where gypsum is formed in soils that contain carbonate from eolian input; 2. The formation of gypcretes is very slow as is deduced from gypcretes on river terraces with an age of 10 ka BP; 3. The gypcretes document that during the last 100,000 years, at least, no major humid phases interrupted the gypcrete development; 4. The paleoclimatic interpretation of the gypcrete profiles shows that more than 100,000 years the central Namib Desert experienced an arid climate; this is supported by other evidence.

INTRODUCTION AND REGIONAL SETTING

The Namib Desert extends for over 2000 km along the west coast of southern Africa from 14°S to 32°S. Inland, it is bounded by the Great Escarpment, which lies 120-180 km from the coast and forms the western edge of the interior plateau of southern Africa (Fig. 1). In the central Namib Desert, the Swakop and Kuiseb River valleys are deeply incised into bedrock. The latter separates the relatively flat gravel plains with inselbergs to the north from the coast-parallel linear dunes of the Namib Sand Sea to the south. The plain of the central Namib Desert rises with ca. 1° inclination from sea level to about 1000 m a.s.l. at the foot of the Great Escarpment. This plain is called the Na-

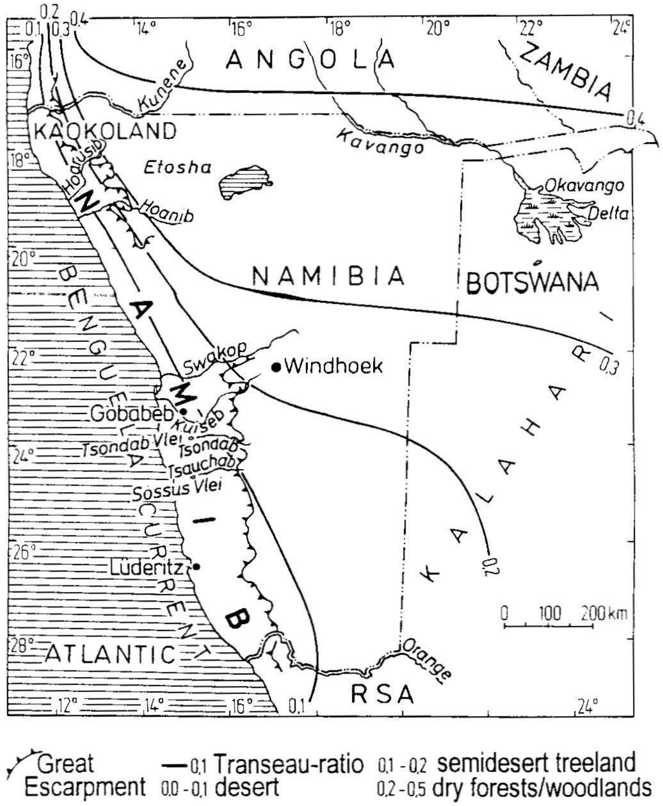


Figure 1. Map of southwestern Africa. The quantitative calculation of the hydroclimatic zonation is based on the Transeau-ratio (= the quotient of the mean annual totals of precipitation and potential evapotranspiration, see Henning 1994).

mib Unconformity Surface (NUS). Age and origin of this inclined plain have been discussed repeatedly. It was formed by long continued erosion across Precambrian/Cambrian metamorphic and intrusive rocks, thus separating these bedrocks from all younger deposits (Ollier 1977).

Whether more humid phases occurred in the Namib Desert and surrounding areas during the Upper Pleistocene has been discussed recently by different authors (Heine 1992, 1995, Rust 1989, 1994, Teller et al. 1990, Geyh 1995). Although landforms, sediments, paleosols, and speleothems are archives containing paleoclimatic information, most data concerning the climatic history in south-western Africa are inconsistent and only conditionally useful for chronological interpretation (Heine 1995). All paleoclimatic data point to a relatively arid climate in the central Namib Desert. Since the Last Glacial Maximum, this part of the Namib Desert was not affected by more than the current average rainfall. Fluctuations in precipitation are super-imposed, but these fluctuations did not lead to a decisive change of the general climatic regime.

Until now, no research work has been carried out concerning the gypcrete soils of the central Namib Desert with respect to their implications to the Late Quaternary climate. Gypcrete soils cover huge areas of the Namib plain and appear to be important archives containing information about the processes of planation and their age. Here we show that in the hyper-arid Namib Desert, in the area between the Kuiseb and Swakop valleys, these gypcrete soils also reveal the possibility of reconstructing the climatic history of the central Namib Desert for the Late Quaternary.

THE STUDY AREA

The study area encompasses a strip in about 400-450 m a.s.l. along a northward leading track of 23 km length, beginning at Gobabeb (see Figs 4 and 5). The distance to the coast is 60-70 km. The area shows a distinct relief and is subdivided by us into six different geomorphic units that are characterized by the occurrence of the same meso- and microforms.

A prominent ascent of about 25 m is the most striking relief feature (Fig. 5); it is bound to a fault of unknown age (post Damara) that has developed in Damara-granites (Sawyer 1974/75). The parent rocks of the entire study area are composed of different types of granite that originated during the Damara-Orogeny (ca. 620-520 Ma ago, Stanistreet et al. 1991). Three large dryland channels (Soutriver [= saltriver], Aussinanis, and Aus) cross the area of investigation. Some channels show distinct erosion terraces several meters high. Besides these more distinct river valleys, the entire plain is covered with a closemeshed pattern of small rills and channels. These features are best developed between the Kuiseb and Soutriver. Channels with a width of about 10 m can extend over several, sometimes even dozens of kilometers. Some of them are slightly incised and in a few cases prominent terraces have been developed along the channels. However, most channels are not incised into the gravel plain and they only may be recognised by the desert pavement that shows a slightly altered arrangement and composition of the material. They are 0.1 m to a few meters wide. They are not orientated towards the more prominent drainage lines but cross each others course irregularly. After a length of a dozen or some hundreds of meters their course finally vanishes into the ubiquitous desert pavement. The desert pavement is a stony surface generally composed of a layer of subrounded gravels or coarse sand sitting on a mantle of finer stone-free material. In the central Namib plain, eolian-derived sand is found in small hollows between the clusters of clasts. The sand has a colour of 7.5 YR 4/4 near the Kuiseb valley and of 10 YR 4/4 further to the north. This colour matches the colour of the sand further south, and we attribute the source of the eolian sand to the Namib Sand Sea in the south. Rock outcrops are another common feature of the study area. In most cases they form flat domed shields covering only a few square meters, whereas in geomorphic unit 1 they form numerous half-spheres, reaching heights of up to 2 m. All outcrops show distinctive weathering characteristics with exfoliation, desquamation, lamination, and the formation of tafoni and of a so-called 'ground level platform' (Ollier 1978). The ground level platform describes weathering processes that terminate when the plains' level is reached. Numerous outcrops actually show a ring of weathered grit and sit on a platform of almost unweathered rock. An additional geomorphic feature occurring in geomorphic unit 5 are low dolerite dikes, striking SSW-NNE. The dolerite outcrops are intensely polished by NNE to E winds and show a blackish rock varnish. They disintegrate into individual blocks.

The climate of the central Namib Desert is arid to hyper-arid but, especially in the coastal area, relatively cool. A major feature of the region is the steep climatic gradient from the cool, foggy hyper-arid coastal zone to the hotter inland areas towards the Great Escarpment which receive scant summer rainfall. Mean annual rainfall increases from 15 mm or less at the coast to 27 mm at Gobabeb and 87 mm at Ganab (east of the Langer Heinrich Mountain). Two types of rain occur in the central Namib: (1) Locally limited high-intensity storms, and (2) Extensive long lasting low-intensity rains (Sharon 1981). In the period between the 24th Dec. 1992 and the 30th Mar. 1993 24 rain events were recorded. Although rain gauges did not record any rain the topsoil was moistened to a depth of at least 2 cm. Two Type 1 storms in the same period yielded a total precipitation of 12.4 mm within just a few minutes. Advective fog is a distinctive feature of the Namib climate (Lancaster et al. 1984). The amount of fog precipitation balance out the rain precipitation fairly well. Within the study area fog precipitates on 50 days a year (Olivier 1995, Lancaster et al. 1984). Fog frequency is decreasing rapidly to the east. The study area is close to the eastern limit of regular fog occurrence and the distribution of gypsum soils as well. About 10 km east of Gobabeb no gypcretes are developed on the plain.

SOURCES OF DATA

Sources used for this study were 1:50,000 scale aerial photographs, 1:50,000 scale topographic maps, ca. 1:70,000 scale simplified geological map elaborated by Ward (unpublished), and the soil map of Scholz (1972) (Fig. 3). During this study emphasis was placed on fieldwork. The sites of the soil pits were carefully chosen after a survey of the study area and the interpretation of the maps with regard to different geomorphic features.

Profile pits about 1 m^2 wide were dug down to the bedrock or to massive carbonate cementation. The geomorphological situation of the surrounding area of each soil section was studied in detail and relief characteristics were recorded. The composition and the appearance of the desert pavement was noted. The different soil and sediment horizons were documented with additional descriptions of each physical feature that would not fit into a mere pedologic key. Carbonate was tested by using 5% HCl. Soil colours (moist) were recorded with the Soil Colour Chart of Oyama and Takehara (1970). Texture, structure, and density of the single layers were determined. The soils were characterized by using the German nomenclature according to 'AG Bodenkunde' (1982). Special attention was paid to density, size, purity, colour, and form of gypsum aggregates and to the distribution of gypsum crystals throughout the entire sections.

Other data sources used for this research were samples that were taken from most localities. Big aggregates of the soil were recovered from the pits to study the features of the gypcretes in detail. The pits were refilled and the surface structure was carefully rearranged. Samples of six sections (1, 2, 4, 10, 16, A) were brought to Germany for laboratory analysis.

The material <2 mm was sieved to gain the coarse sand fractions (0.63-2 mm). Hard cementation of some samples did not allow to obtain a representative sand fraction. By using a binocular microscope each fraction 0.63-2 mm was analysed according to colour, mineral type, roundness, and purity of quartz grains. There was no chemical treatment of the material in order to preserve the salt and gypsum crystals, the coatings of the sand grains etc. The sand fraction was then classified into different groups with similar characteristics. This technique made it possible to distinguish different strata. To determine the minerals X-ray diffractometry (*RDM Siemens D 5000*, copper radiation) was applied to powder samples. The grain analyses under the microscope together with the X-ray diffractometry yield to obtain a classification of 17 groups that differ from one another with respect to colour, mineral content, roundness etc. Furthermore, pH values and the amount of $CaCO_3$ were determined. Measurements of the electrical conductivity were carried out.

CLIMATIC AND GEOMORPHIC HISTORY OF THE NAMIB PLAIN

The central Namib plain is a pediplain. Ollier (1977) referred to this erosional feature as the Namib Unconformity Surface (NUS). It is believed by some researchers to have formed or to have been exhumed during the Late Cretaceous, initiated by the opening of the southern Atlantic Ocean. The plain itself developed as a result of scarp retreat of the Great Escarpment that formed the

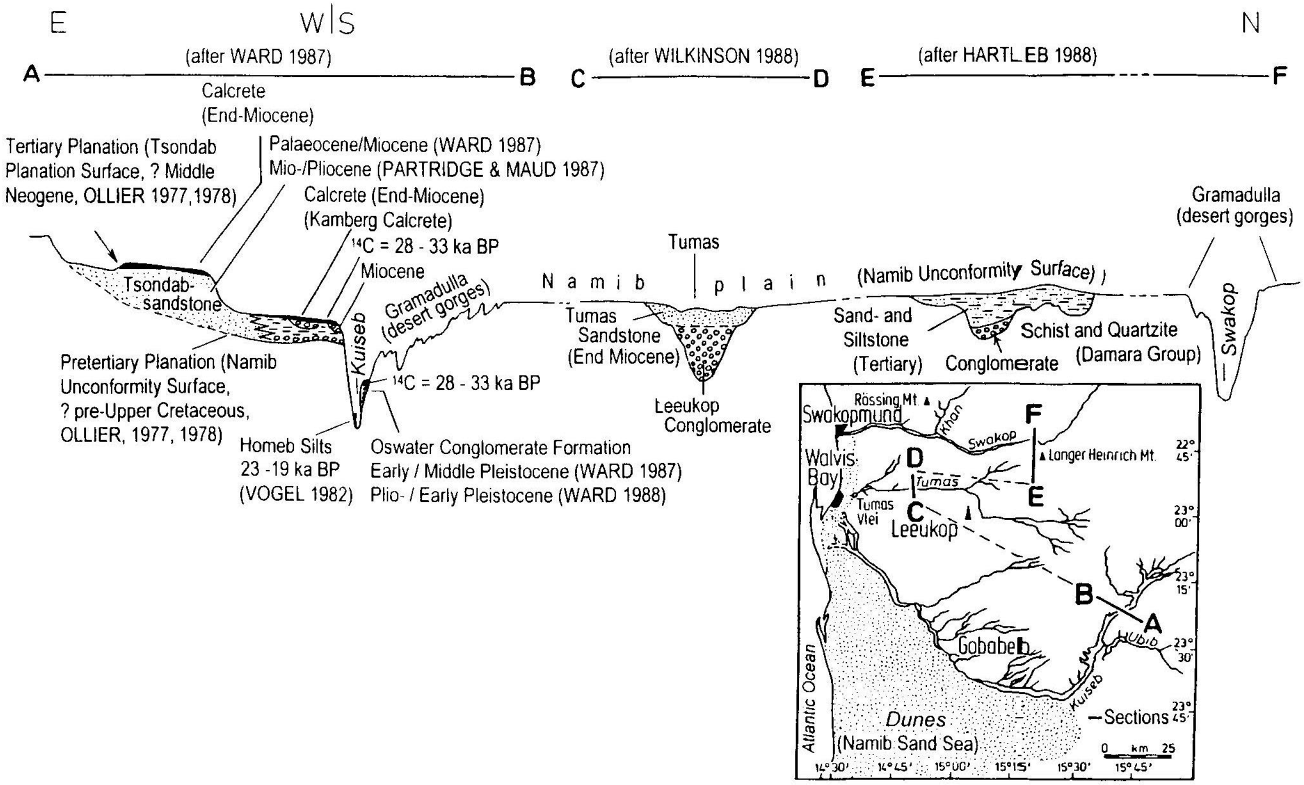


Figure 2. Cenozoic erosion and accumulation cycles in the Tsondab/Kuiseb, Tumas and Swakop area after different authors.

eastern shoulder of a rift valley. In the east and south of the Kuiseb the NUS is commonly overlain by the Tsondab Sandstone Formation that documents the existence of a widespread sand sea in the Early Tertiary. After its formation this early erg was partly eroded probably due to fluvial activity shaping the Tsondab Planation Surface (TPS, Ollier 1977). The deep incision of some rivers and the refill of their valleys with coarse gravels probably dates back to the same period. The distribution of the Tsondab Sandstone almost coincides with the area covered by the modern erg. The Tumas Sandstone Formation of the Tumas river area has been correlated with the Tsondab Sandstone Formation (Ward 1987, Wilkinson 1988, 1990). The sandstones filling the bedrock depressions of the central Namib plains (Fig. 2) are covered by pedogenic calcretes that formed prior to the deep incision of the Swakop and Kuiseb drainage systems west of the Escarpment (Ward 1987). This formation of the so-called Kamberg Calcretes (Yaalon & Ward 1982) marks the last important evolutionary stage for the relief in the central Namib. In some areas these calcretes are very thick and did preserve the relief that was bevelled by the pediplanation processes associated with the formation of the TPS and the NUS, respectively. The pedogenic phase of calcrete formation ended when the Benguela current was fully established about 10 Ma ago. This led to renewed aridity in the Namib Desert. Since that time, no significant geomorphologic evolution has occurred in the central Namib Desert (see Fig. 2), apart from the deep incision of the Swakop and Kuiseb drainage systems (gramadulla relief).

The development of the geomorphic features of the central Namib Desert has been investigated by different authors. Besides other criteria, differences in weathering processes led Besler (1972) to distinguish three climatic-geomorphic zones. Hövermann (1978) and Ollier (1977, 1978) studied modern geomorphic processes on the well-planed surface while others (Goudie 1972, Ollier & Seely 1977, Selby 1977a, b) described several single phenomena. The first and to date only comprehensive study to combine presently active processes with the complete record of landscape evolution was elaborated by Hövermann (1978, 1985). Apart from Hövermann the authors neither considered active geomorphic processes on the plain younger than the formation of the Kamberg Calcretes (Ollier 1977, 1978, Ward 1987, Besler et al. 1994) nor did they consider and record wide areas primarily formed by alternating fluvial and eolian processes as described by Hövermann (1978) (e.g. Carlisle 1978, Hambleton-Jones 1983, Rust 1989, Wilkinson 1990).

The results of Hövermann (1978: 60-63) are summarised briefly below. The Namib plain is a sandy desert plain ('Sandschwemmebene'). Sandy desert plains are characteristic features in altitudes of ca. 300-900 m a.s.l.. The central Namib plain represents an active and inclined denudational land surface with active channels. These channels pendulate on the plain's level removing material from the entire surface. Through this kind of fluvial transport, 'funnel-shaped' (Hövermann 1978) surface areas evolve, several km^2 wide, narrowing towards the direction of inclination. These landforms alternate with conical-shaped areas of similar size, where the material that was removed from the funnel areas is temporarily deposited. Funnel- and conical-shaped areas are short-lived forms controlling each other in their (re-)formation. These processes are the result of fluvial activity (maximum vertical relief differences do not exceed a few meters) leading to a distinct differentiation of surface microforms. Subsequent eolian activity is smoothing and levelling these differences. According to Hövermann, the combination of short fluvial modelling events and long-lasting eolian levelling leads to the denudation of the plain as a whole and is counteracting the marked incision and evolution of distinct channels. Therefore the pre-existing dominating plain form remains unchanged. Consequently downwearing is presently the only mechanism affecting the plain. Only at its margins it is being destroyed by slow scarp retreat of the desert gorges (gramadullas).

According to Rust (1989) insignificant sheet wash erosion occurs on the central Namib plain; he notes that there is no evidence of an altidudinal belt with sandy desert plains as described by Hövermann (1978). Wilkinson (1990), too, cannot corroborate active denudation processes in the area of the Tumas River which was mainly formed by fluvial activity. The evolution of the Tumas river system and the incision of the river itself occurred during slightly moister climatic fluctuations. Wilkinson (1990) postulates only little eolian activity during Upper Pleistocene and Holocene times. Furthermore, the Tumas River is incised markedly only in some passages of its course. The longitudinal profile depends mainly on the plain's inclination. Remnants of planed surfaces which are cemented by gypsum are found in different altitudes above the present valley bottom. They do not give proof of the plain's denudation but are interpreted by Wilkinson as short phases of incision during increased fluvial activity. Wilkinson concludes that increased rainfall in the rivers' catchment area close to the Great Escarpment led to high runoff values. Phases of incision are linked with these periods of higher rainfall; it is likely that they represent the pedogenic phase of the Kamberg Calcrete Formation.

The climatic development of the central Namib Desert during the Late Cenozoic is rather well established (Fig. 2, Besler et al. 1994). The Namib is characterized by a climate that has been more or less arid for approximately 40 million years. Marine pollen assemblages in cores off the coast document arid climatic conditions along the coast ever since Pliocene times, but there is still a lack in a more detailed knowledge as far as the Late Quaternary is concerned. No long terrestrial sediment sequence occurrs in the Namib plains, because this area underwent almost continuous denudation since pre-Tertiary times. An analysis of the paleoclimatic information from landforms, paleosols, sediments, and speleothems in south-western Africa shows that only few data concerning the climatic history are useful (Heine 1995). Many problems hampered the geochronological and paleoclimatical interpretation of the ^{14}C, U/Th, and TL dates (Geyh 1995) that were elaborated by investigations in areas adjacent to the central Namib gravel plain (e.g. the Kuiseb valley: Vogel 1982, Heine 1987, 1990, Smith et al. 1993, the Namib Sand Sea: Rust 1989, Teller et al. 1990, the Rössing Cave: Heine & Geyh 1984, Heine 1991, 1992). We consider the central Namib to have been arid throughout the Quaternary with only a few fluctuations to slightly moister conditions. It is assumed that the most recent of these fluctuations occurred during the Late Pleistocene/Holocene transition, during the oxygen isotope Stage 3 (>25 ka BP) and, possibly, during oxygen isotopic Stage 5 + 7 (?).

GYPCRETE SOILS

General

According to Watson (1985) gypsum crusts occur in warm desert environments receiving less than 250 mm of rainfall per annum. They are located down to a depth of 10 m below the surface. They consist of gypsum accumulations 0.1 m to 5.0 m thick, with more than 15% by weight gypsum and at least 5% by volume more gypsum than the underlying horizon. In the present study we concentrate on genetic aspects of gypsic crusts, hence even initial gypsum formation showing only a slight increase in pedogenic gypsum is termed 'gypsum crust' or 'gypcrete'.

The gypsum crusts of the Namib plain show a quite typical occurrence: at the coast they form a continuous cover up to 4 m thick (see Martin 1963). Towards the interior their thickness is steadily decreasing, until they finally occur only in small patches, imbedded in the surrounding gypsum-free area. According to Besler (1972) the easternmost distribution of gypcretes is at a distance of approximately 50-60 km from the coast. This is about the same distance fog regularly advances inland from the Atlantic. The inland limit of gypcrete occurrence matches the 50 mm limit of precipitation (rain and fog) fairly well. From 1962 to 1984 the yearly average amount in rainfall was 24.5 mm and 31.5 mm fog respectively, measured at the Desert Research Station Gobabeb.

Morphology, chemistry, and origin of gypsum crust occurrence has been investigated by Watson (1985, 1988). Limiting factors of gypsum crust formation are temperature, evapotranspiration, and the annual amount of precipitation. If soil moisture is too high gypsum will be dissolved and precipitation of gypsum crystals is prevented. On mobile substrates (e.g. dune sands) no gypsum crusts are formed. Gypcretes in places where no gypsiferous bedrocks are present indicate arid climates, as is the case in the central Namib (Watson 1985, 1988; see Wilkinson 1990 for limited occurrences of gypsum rocks).

Watson (1979; see also Dixon 1994b) recognised three principal types of gypsum crust: a) Evaporitic crust characteristically consists of packed microcrystalline gypsum strata; b) True gypsum or 'croûte de nappe' occurs in two forms: either as lightly cemented gypsum crystals up to 1 mm in length commonly developed beneath non-gypsic sediment or as desert rose crust consisting of interlocking lenticular gypsum crystals ranging in size from a few millimeters to 20 cm; c) Surface crust also occurs in two forms: gypsum powder which is composed of loose accumulations of small gypsum crystals, and indurated crust which is characteristically polygonal or columnar in appearance. In the central Namib Desert, Type b (highly cemented gypsum crystals beneath a non-gypsic sediment) is the characteristic gypsum crust which has a wide distribution.

Reheis (1987) described gypsum accumulations in soils (in the Rocky Mountains) in terms of a morphologic sequence. Reheis (1987 cit. after Dixon 1994b: 98) identified four stages of gypcrete development. 'Stage I gypcrete is characterised by thin, discontinuous gypsum coatings on the undersides of stones. Stage II gypcrete has abundant gypsum pendents under stones and gypsum crystals scattered through the matrix or forming small, soft powdery nodules. Stage III gypcrete is distinguished by the presence of continuous gypsum through the soil matrix and large gypsum pendents beneath stones. Stage IV gypcrete consists of a continuous gypsum-plugged matrix, with stones and smaller debris floating in the gypsum matrix.'

The origin of the gypcretes found in the study area is not yet completely understood. We join the interpretation of gypcretes by Martin (1963) who argues that fog precipitation is the main source of sulphur. For the gypcretes of the central Namib Desert, most authors agree with Martin's (1963) model of gypcrete origin: The Namib gypcretes are of pedogenic origin, resulting from the downward movement of gypsum; the source of gypsum is regarded as eolian (see Besler 1972, Carlisle 1978, Hambleton-Jones 1983, Watson 1985, 1988, Dixon 1994a+b).

For the central Namib Desert, only Wilkinson (1988) emphasizes the possibility of different geogene sources of sulphur; however, those are only confined to local occurences. Ocean basins stretching parallel to and closely along the coast are described by Hambleton-Jones (1983). They show an extensive anaerobic milieu and therefore produce large amounts of H_2S. This gas is oxidated to sulphate while it ascends to the ocean surface. Winds blowing inland pick up sulphate molecules directly from the sea water. Dissolved in the fog sulphate molecules are carried eastward and are precipitated on the desert plain where they are deposited together with carbonates that are derived from the bedrock and/or eolian input in connection with dust transport from the east (Namibian Highland, see Eitel 1993, 1994). After rains or high fog precipitation in the desert, within the moistened topsoil the ubiquitously occurring carbonates are dissolved. As a result Ca-ions are available and gypsum is formed preferentially (see Watson 1985). The high solubility of gypsum is responsible for the enrichment of gypsum within the entire soil sections. Even a low soil moisture content can cause horizontal and vertical movement of gypsum. Therefore the formation of most gypcretes in the central Namib Desert is explained by a per descendum model (Wilkinson 1990). The dissolved gypsum ions infiltrate the soil and crystallize in the lowest part of the moistened substrate. In many sections, carbonate-cemented layers are situated directly beneath the gypcrete horizons. East of the area of gypcrete occurrence, carbonate-rich layers form the common calcretes as described by Blümel (1981). Because of the characteristic features of the gypcretes, they appear to be very useful indicators for arid climate and morphodynamically stable conditions (see Watson 1985, Wilkinson 1990).

Soils of the central Namib Desert

Raw mineral soils, calcretes, and gypcretes are the most important soil types of the central Namib Desert. South of the Kuiseb, sand desert soils are found. Most of the soils have a light brown (7.5 YR 4/4, top soil) to yellowish brown (7.5 YR 6/6 to 10 YR 4/4-6/6, gypsum layer beneath top soil) colour and are shallow, with an underground horizon which may consist of calcrete, gypcrete, or salt (Scholz 1972).

Only Scholz (1963, 1968, 1972) investigated the soils of the central Namib Desert near Gobabeb. He distinguishes between soils of the dune area, soils of the valleys, and soils with crusts in the plains (Fig. 3). Most of his soil sections are located either in somewhat exceptional positions (salt crusts of river beds) and/or outside our study area. Because of the distance from the Atlantic Ocean, gypcretes do not occur as thick continuous layers, but as thin, only slightly cemented horizons. Since Scholz (1963, 1968, 1972) major objective was to present a first description of the different desert soils, he neither investigates the origin of the gypcretes in detail nor the processes of crust formations and mobilisation of dissolved ions. Nevertheless, his observations about the Namib soils are of great value. In using the Namib gypcretes as paleoclimatic indicators, the present study goes beyond the purpose of Scholz.

The gypcretes of the central Namib Desert

25 sections were recorded in detail. The gypcrete Sections A to F and 1 to 17 are located on the plain, the Sections 18 and 19 on the northern bank of the Kuiseb in the canyon area east of Gobabeb (Figs 4 and 5). Relations between the development of pedogenic crusts and their occurrence on the plain, on slopes, and in channels and valleys were of special interest for our study. Therefore the site of each soil profile was selected very carefully. In each profile, the vertical distribution of gypsum was recorded.

A detailed investigation of the desert soils with respect to the meso- and

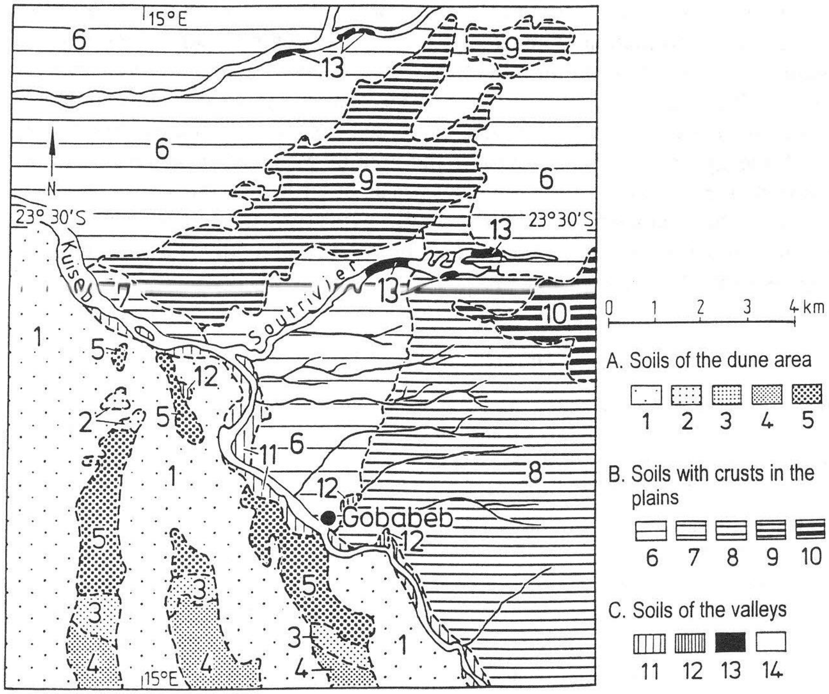


Figure 3. Soils in the vicinity of Gobabeb, central Namib desert (adapted from Scholz 1972).

A) Soils of the dune area. 1. Vegetationless sands forming dunes which are still in motion. The sands consist mainly of quartz and feldspar grains, 2. Young soils with calcium carbonate concretions and crusts in depression of dune valleys, 3. Fossil, cemented red-brown aeolic sands, partly eroded, containing gypsum and single calcium carbonate concretions, 4. Cemented red-brown aeolic sands with surface crust of calcium carbonate and gravel blanket, 5. Ochre brown limestone soil and calcareous gypsum soil above granite with a blanket of grit and a large proportion of aeolic sands in the upper horizon.

B) Soils with crusts in the plains. 6. Shallow, ochre brown calcareous soil with a slight gypsum crust above granite and with a grit blanket; also Syrosem of granite, 7. Ochre brown salt containing gypsum soil on granite and with a grit blanket, 8. Ochre brown calcareous gypsum soil on metamorphic schists, with a grit blanket; also shallow gypsum soil on pegmatites, rich in detritus, 9. Ochre brown calcareous soil on granite, with grit blanket and with gypcrete at surface, 10. Ochre brown, partly calcareous gypsum soil with grit blanket and buried red-brown soil.

C) Soils of the valleys. 11. Young brown flood-loam rich in mica bordering the Kuiseb river bed and overgrown with trees, 12. Fossil dark brown remains of flood-loam on high level terraces, mostly incrusted by salts, 13. Dirty brown, salt containing soil of various rivers, with a polygon crack pattern on the surface formed by underground water, 14. Riverbeds, partly choked with eroded desert detritus, partly with light coloured quartz sands.

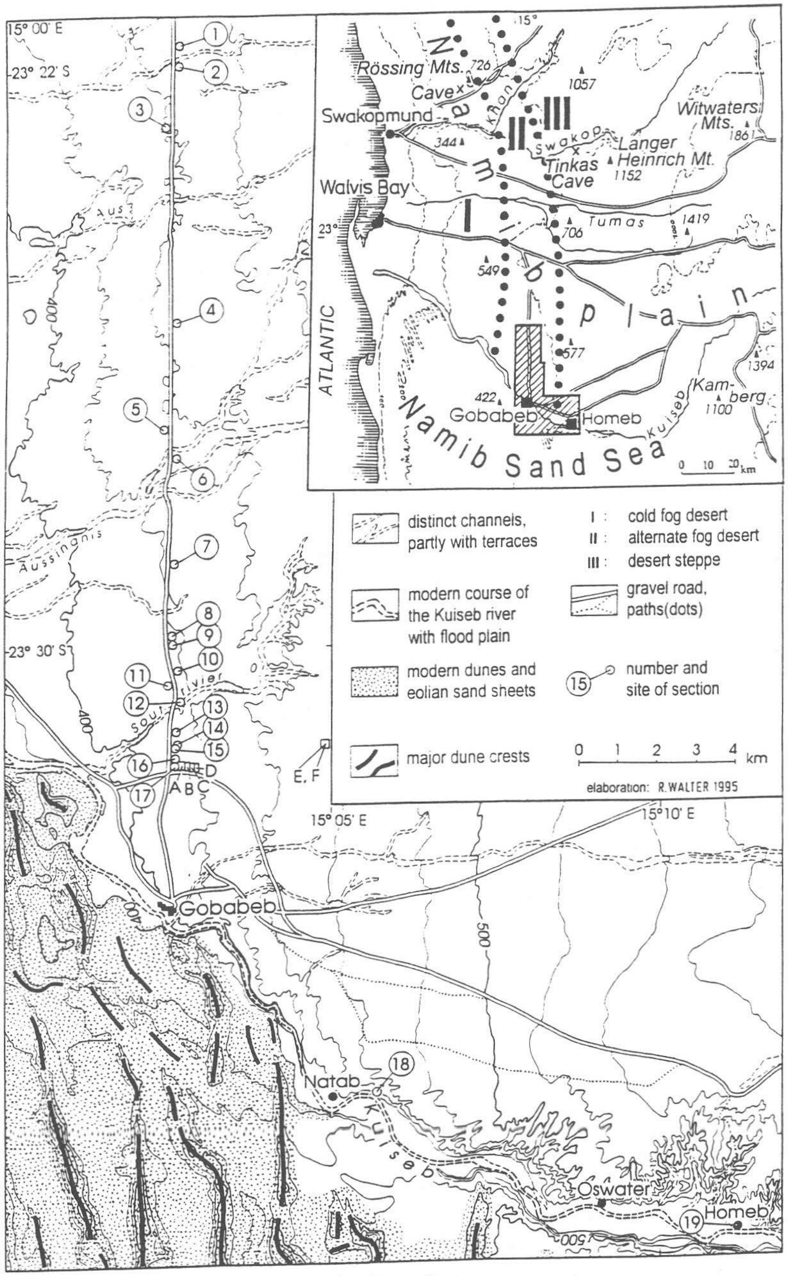


Figure 4. Sites of gypcrete sections in the study area.

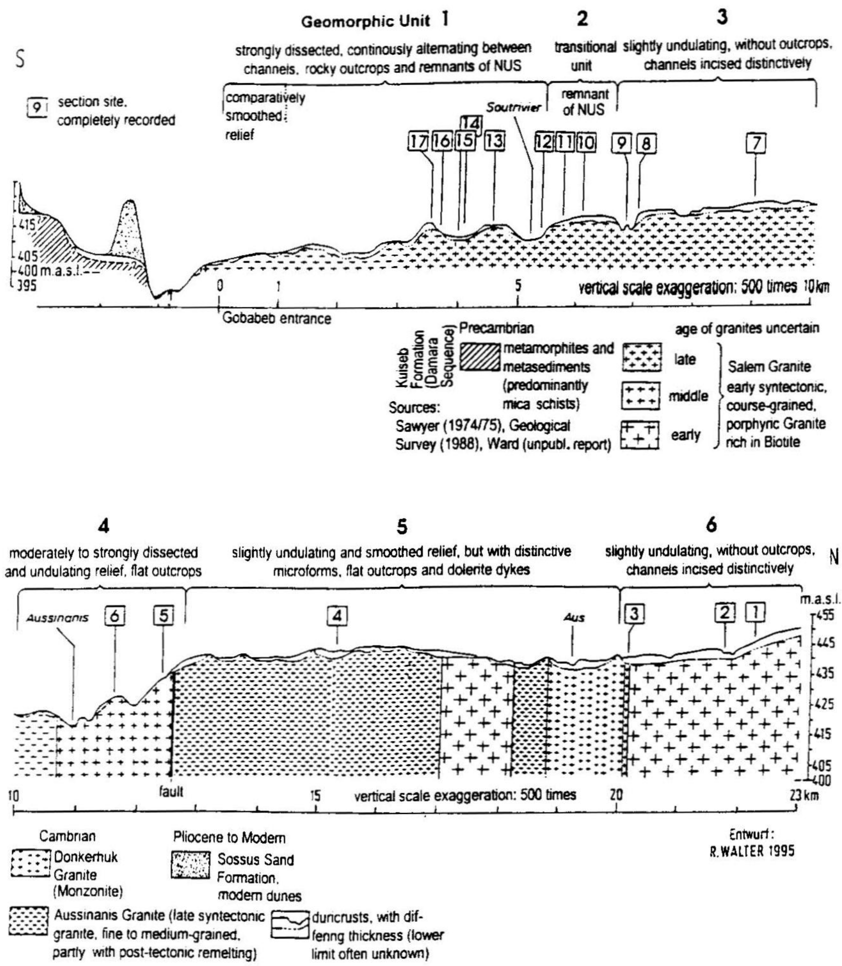


Figure 5. Geologic-geomorphologic section of the study area.

microrelief north of the Namib Desert Research Station of Gobabeb (Walter 1994) yields a distinction of different phases with characteristic pedogenic processes. A schematic soil profile of the central Namib gravel plain shows from top to bottom the following soil horizons: (1) Layer of 2-3 cm of eolian material, with a desert pavement (quartz, rock fragments, feldspar, remnants of calcrete, etc.), composed of a layer of angular to subrounded gravels one or two stones thick sitting on a mantle of finer stone-free silty sand; (2) Gypsum crust of varying thickness; in the upper part characterized by pendents of fresh gypsum minerals (Stage I after Reheis 1987) that formed on top of cone-shaped gypsum aggregates; these form a gypcrete, consisting of a continuous gypsum-plugged matrix, with stones and smaller debris floating in the gypsum matrix (Stage IV after Reheis 1987); (3) Gypsum crust mixed with weathered carbonate cementations, calcretes, or decomposed bedrock (Stage III to IV after Reheis 1987); (4) Horizon rich in $CaCO_3$ or/and decomposed bedrock with gypsum minerals formed by crystallisation from descending soil water; (5) like (4) but without (visible) gypsum; (6) Bedrock or calcrete.

On the Namib plain no open pits or walls expose a complete stratigraphy from bedrock to the desert pavement on the top layer. Therefore it is still questionable, whether the calcretes mentioned under (6) are real calcretes or not. We assume that they form 'real' calcretes, because stratigraphically they can be correlated with the Kamberg Calcrete in the east and the calcretes close to the coast in the west mentioned by Martin (1963). If our correlation is correct then the massive calcareous layers of the study area are of Miocene age. They are likely to form the widespread erosion surface on which the Quaternary processes occurred. In the Namib plain, the existence of the calcrete layers on top of the (decomposed) bedrock document, that calcrete formation occurred after the planation of the central Namib Desert. Since calcrete development is only possible under more humid climatic conditions compared to today and since no calcrete pedogenesis is reported in the central Namib Desert during the Quaternary (Ward 1987), we believe that the calcretes of our soil sections date back to the Late Tertiary.

The soil Sections 1, 3, 7, 8, 9, 10, 11, 13, 17, A, C, E, F are fully developed soils because they show the characteristics of the schematic gypcrete profile described above (Fig. 6). In the Sections E and F visible remnants of carbonate cementations were not observed; in some parts, however, the soil is extremely rich in carbonate. We believe that this carbonate is relict and related to older carbonate cementation horizons (4). In Section C, located in the middle of a 2 m wide channel, neither cone shaped aggregates of gypsum nor fresh gypsum crystals are found; the gypcrete starts abruptly in a depth of 12 cm. This is probably due to the position of the section in the middle of a channel, where scouring processes lift or drag the uppermost 12 cm of material. For this geomorphological position a temporarily increased water supply is assumed. A similar situation applies to Section 4; it is located within a paleochannel, several meters in width. Here, in a depth of 20-25 cm the upper part of an extremely compact gypcrete was excavated. Its surface appears to be polished. The original structure and the former arrangement of the single gypsum aggregates can be reconstructed by macromorphological investigations. The gypsum aggregates are related to rhythmical curvatures of the crust's surface. On top of the crust at least three different sediment layers are found that are bedded prominently. The uppermost sandy layer overlies the sediments concordantly. The bedded top layers show a progressive increase in carbonate

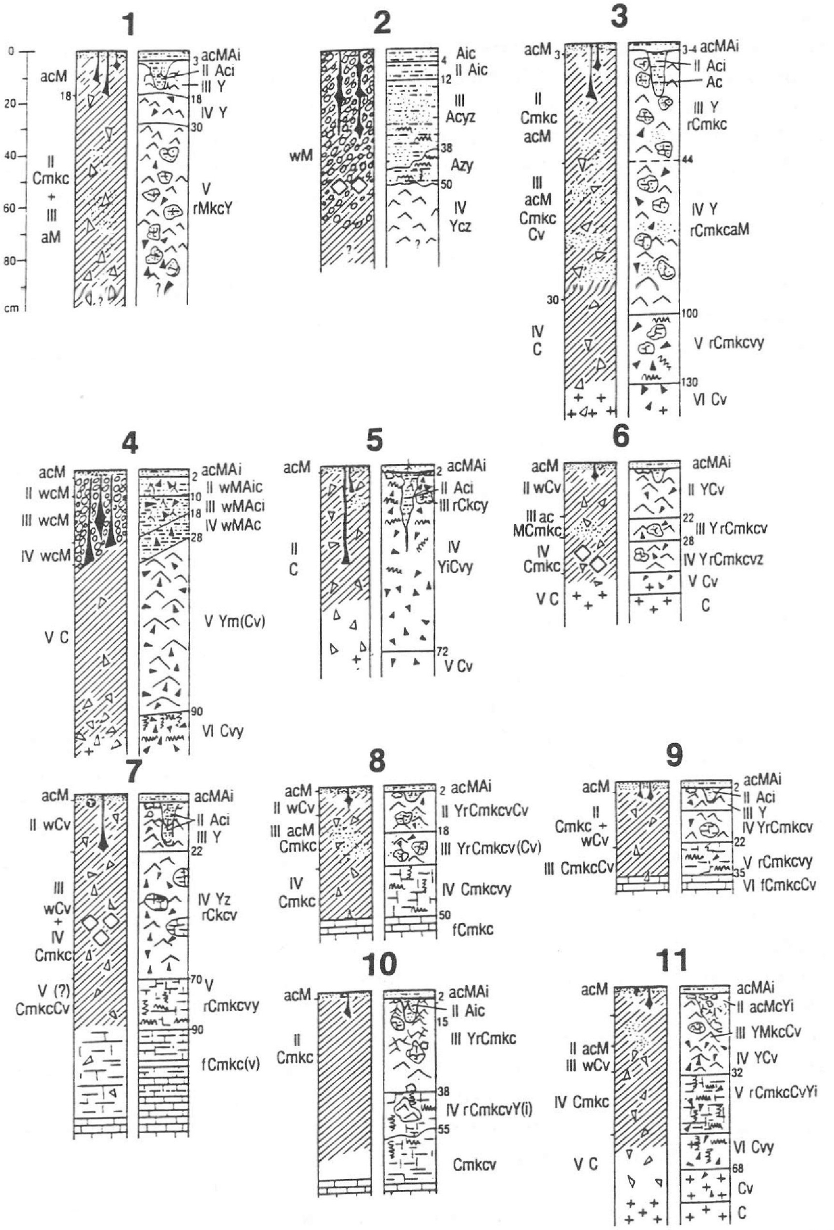


Figure 6. Sections of gypcrete soils (symbols after Bodenkundliche Kartieranleitung, 3rd edition, Hannover/Germany 1982).

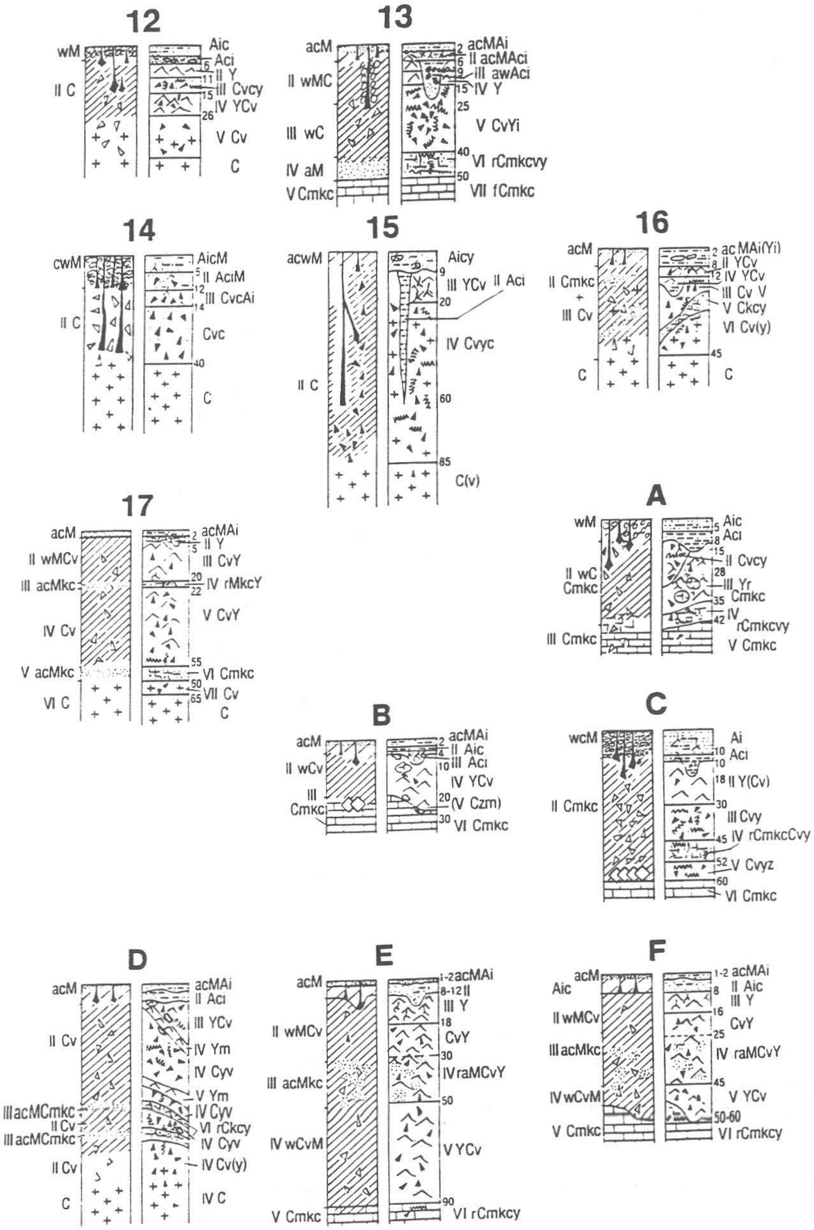
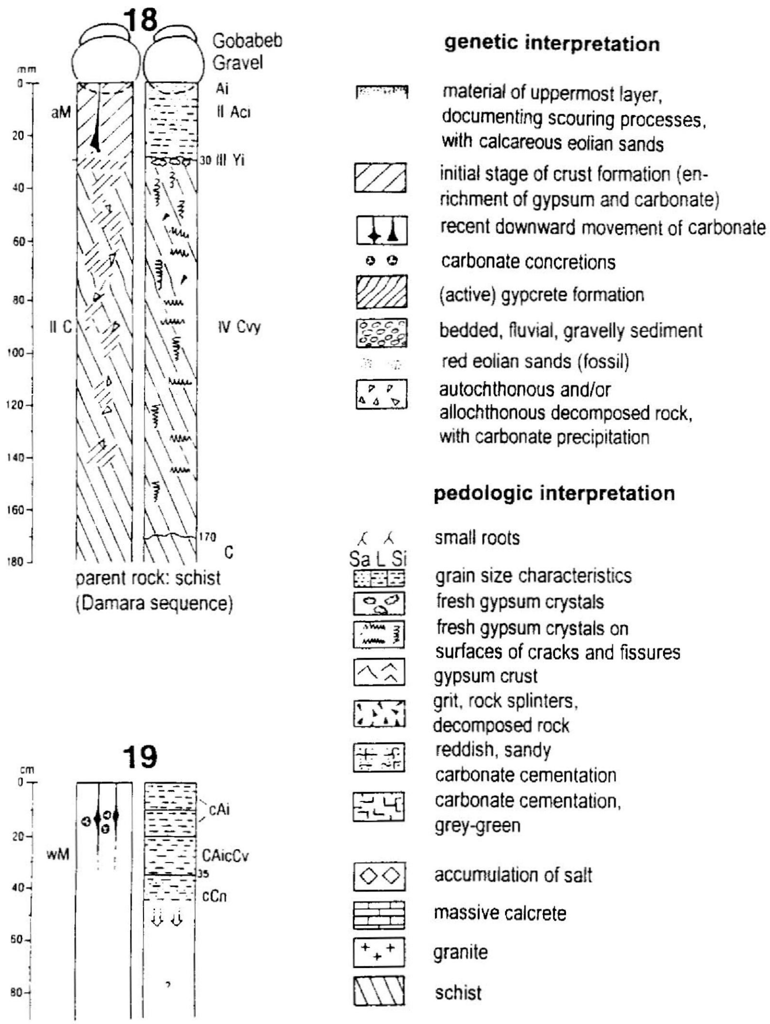


Figure 6. Continued.



most important symbols used to characterize different horizons:
acMAi = mixed material, eolian calcareous sands (acM) showing initial alteration due to pedogenesis (Ai)
Cmkc = massive concretional carbonate (cementation, calcrete)
a = eolian transport
w = probably moved by scouring processes (w = water)
M = weathering products from different parent material (mostly sand and grit)
Y, y = gypcrete layer, gypsum enrichment
z = salt enrichment

elaboration:
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Figure 6. Continued.

from the surface down to the gypcrete. In Section 2, also showing an increase in the amount of carbonate precipitation with depth, three different enrichment units of carbonate, gypsum, and halite occur. This section is located on a low terrace of a small river; the material consists mainly of colluvial sands and gravel. The development of thin salty layers depends on the geomorphological position of the soil section. Platy, indurated salt crusts several cm thick are formed where shallow rock bars dam episodic groundwater flow in channels and gullies (see Scholz 1968, 1972). In Section B such a pure salt crust overlies a massive calcrete. Although Section B is only 30 cm deep, it shows a fully developed soil profile as given by the schematic section mentioned above.

Section 12 is located on the slope (ca. 20° inclination) of the northern bank of the Soutriver. The section is located about 1m above the valley bottom. No river terraces can be observed in this area; it is in a small channel at the foot of a slightly weathered granite outcrop that rises up to 3 m above the river bed. Despite this extreme geomorphic position the gypcrete profile is fully developed; it is striking that the different layers are very thin. Beneath a four cm thick colluvial top layer fresh gypsum crystals are accumulated. This layer turns into a gypsum crust containing colluvial material. The horizon underneath is made up of decomposed rock and it is enriched in gypsum; a sudden increase in carbonate characterizes the lower part of it. The base is made up of a compact gypsum crust with a sudden increase of carbonate where the crust turns into granite.

All other sections differ more or less significantly from the schematic idealised section. The pit of Section 14 was dug in the upper reach of a small channel originating on a flat shield of granite that is just 1 m away. Section 14 shows a bedded top layer with parautochthonous, gritty gravely sediments overlying a similar horizon which turns into unweathered granite. The complete section is free of gypsum. Section 15 is located in a similar position, yet not located in a channel. That is the reason why no sediments moved by scouring processes are present and why small gypsum crystals could form very close to the surface. Beneath this layer a compact gypcrete occurs resting on in situ weathered granite. The granite is decomposed to a depth of 85 cm, showing aggregates that are laminated parallel to the surface. Thin discontinuous coatings and filaments of gypsum are observed on the walls of fissures. Accumulations of carbonate also occur on the surface of fissures. A remarkable wedge reaching to a depth of 60 cm is filled with silty fine earth completely lacking coarse material (>2 mm). The complete wedge is free of gypsum, but it holds the highest content of carbonate of the whole section. Similar observations were made in the pit of Section 5. It is located in a topographic situation similar to that of Section 15. The granite is very fine-grained and completely weathered into single grains. This grit is dominating the Section from 2 to 72 cm, showing finely dispersed gypsum and a few remnants of a pink-coloured cementation of carbonate. There is a remarkable pocket 30 cm wide and 20 cm deep. The filling consists of gypsum-free, sandy, loose material with the generally high carbonate content increasing with depths. Within the loose material a wedge has developed extending into the grit. The lower end of this wedge is surrounded by increasing carbonate impregnation. Although decomposed granite is the substrate of all three Sections (5, 14, 15), only on the surface at Section 15 this material can be recognised. The composition of the desert pavement overlying the Sections 5 and 14 did not differ from the stony surfaces in their vicinity.

Sections 6 and 16 have revealed gypsic soils that look very much alike. Near the surface incipient gypsum formation is evident in the decomposed granite as the main component of soil material. The weathered granite contains veins of carbonate cementations with scattered gypsum crystals.

Section D differs considerably from all other sections with respect to the sequence of layers. Thin laminae of extremely dense gypsum and pink carbonate cementations are separated by horizons of decomposed granite within an indurated matrix. These layers alternate irregularly down to a depth of 90 cm, where the unweathered granite is reached. Around a centre of unweathered bedrock concentric half spheres of granite occur. The voids between these indurated spheres are filled with gypsum in the upper layers and with carbonate towards the lower layers. The upper, 3-4 cm thick gypsum crust dips with an inclination of 30°; it is capped discordantly by the top layer in about 6 cm depth. The desert pavement and the top layer are regularly developed. An investigation of the surface yielded no indication of the exceptional soil profile.

Section 18 is located on a terrace at the northern bank of the Kuiseb river in about 20 m above the floodplain. The terrace is developed in Damara schist, overlain by fluvial quartz sediments of the Gobabeb Gravel Formation. These formations are of Late Pleistocene age (ca. 10 ka BP; Ward 1987). Beneath the well rounded gravels a fine layer of eolian sand only one millimeter thick can be traced. This sand lies on top of a sandy silt rich in carbonate documenting eolian as well as fluvial origin. At the base of the Gobabeb Gravel accumulation, in a depth of three centimeters (!), a lamina of gypsum not even one mm thick marks the transition to the slightly weathered schist. Silty material and scattered gypsum crystals occur in some cracks and fissures down to a depth of 15 cm. Below this depth the schist remains unweathered.

Section 19 is located in the Kuiseb valley close to the settlement of Homeb. It is developed in reworked Homeb Silts that form a terrace dated to 9,6 ka BP (Vogel 1982). The site is outside the area where gypcretes are found; it is east of the distribution of gypsic soils. Pedogenic processes are only documented by slight differences in soil texture and soil density, by downward translocation of carbonate in percolating soil waters and initial development of soil structures. These features of an incipient pedogenesis are confined to a depth of 35 cm. Texture and density differences might be a result of reworking processes of the sediment. There are no other indications of soil formation.

In many sections trough-shaped pockets are common features. Width and depth of these pockets are usually not exceeding 30 cm in either direction. They are found directly beneath the top layer. They are filled with fine-grained material that is bedded concentrically in the troughs. While gypsum is always absent, carbonate is enriched significantly in these hollows. They document 'diapiric' movements in the gypcretes and they may be compared with the 'Leopard's Spots' described by Glennie (1995).

DISCUSSION AND CONCLUSION

The sedimentation of the Homeb Silts occurred between ca. 23 and 19 ka BP (Vogel 1982) or between 18,3 ± 3,4 and 17,4 ± 3,8 ka BP, respectively (Eitel 1994). Reworked Homeb Silts are widespread in the Kuiseb valley; they form pediment terraces that are dated to 10 ka (Vogel 1992, Ward 1987, Heine 1987). The pedogenesis, which affected the 10 ka terraces, is very weak. The calcium carbonate contained within the terrace sediments precipitated only to a depth of 30 cm. In Section 19 (Homeb) the carbonate accumulation only formed faint concretions. The soil development of Section 18, represents the same period that was responsible for the soil development. The time of 10,000 years appears to be sufficient to form incipient clearly visible crystals of gypsum. These represent a first stage of gypsum crust formation. The continuous lamina of gypsum in Section 18 is related to the boundary between the fine-grained silty sand and the slightly weathered schist. A homogeneous substrate would hardly have supported a visible accumulation of gypsum. If in 10,000 years only weak gypsum precipitation occurs, then rough estimates for the periods required for visible alterations due to pedogenic processes can be given, but with the utmost caution. Even if we think of climatic fluctuations during the Holocene and of changing intensities of pedogenic processes in the Kuiseb valley, a period of >5000 years is still required to form the described features. It should be mentioned that the geomorphologic position of the sections exclude pedogenic processes influenced by the Kuiseb river by direct flooding and by groundwater as well. Only the local climatic conditions (precipitation through rain and fog) control the water supply of the soils of Section 18 and 19.

With the pedogenic characteristics of the Sections 18 and 19 in mind a rough calculation of the duration of pedogenic processes in the Namib plain can be proposed. The total amount of gypsum and its distribution within the sections of the study area suggest a period of >100,000 years for the formation of gypcretes. The occurrence of pedogenic processes is documented by the precipitation of carbonate in deep reaching wedges (see Sections 5, 15) and in the numerous pockets. This carbonate cannot be related to calcareous material in the sections and/or in close proximity. We suggest that all of the carbonate necessary for the formation of these calcic layers could be derived from atmospheric dust and calcium dissolved in rainwater (see Eitel 1993, 1994). The increased content of carbonate within the uppermost millimeters of the sections give support to this. An increase in carbonate content above the gypcrete horizon is an additional indicator of atmospheric sources for the carbonate. As already discussed, investigations of gypcretes in the Namib have stressed the importance of wind/fog-derived gypsum. Fog is the most likely medium of sulphur transport. Gypsum is formed using up the ions delivered either by fog (sulphur) or by easterly winds (calcium).

In the study area the gypsum crusts are composed of certain individual units; four stages of gypcrete development can be observed within the sections (Stage I to IV, see Reheis 1987). Close to the surface Stage I gypcrete is formed. It forms on top of large and massive aggregates of Stage IV gypcrete. These massive gypsic layers represent the core of the crust; they show a great variety in thickness (ca. 10-60 cm). The gypsum content is decreasing with depths. Stage III gypcrete is found beneath the core crust; it gradually turns first into Stage II gypcrete and then into single aggregates of Stage I gypcrete. On the one hand fog precipitation supports new formation of gypsum starting from the surface (this process is considered to be the initial stadium of crust formation, even if there is no core crust present), on the other hand gypsum migrates downward by vertical translocation; during this process precipitation of gypsum crystals, solution, and recrystallization can occur repeatedly. Because of the strong hydrophilia of gypsum new crystals preferentially form around existing aggregates. Thus stable aggregates gradually tend to become bigger and denser as a result of a self-strengthening process of gypsum concentration. The formation of gypsum is also increased by the carbonate present in the soil. The fine material of the pockets and cracks is often reworked as indicated by structure (concentric bedding) and texture (fine earth lacking coarse material). Therefore, in these pockets incipient formation and concentration of gypsum crystals are prevented and carbonate becomes enriched. Besler (1972) suggested that the pockets probably form because of the dynamics of larger gypsum aggregates: Swelling and shrinking of gypsum caused by moisture and desiccation appears to be the main factor of pocket formation. When moistened, gypsum is swelling strongly, after drying the size of the aggregates decreases enormously and fine sediments fill the fissures that evolve during the shrinking process. The occurrence of pockets is confined to soils with large gypsum aggregates, and the material in the pockets shows a bedding parallel to the shape of the pocket, which supports the notion of this origin of the hollows.

In the Namib plain, the sections in small channels prove that gypsum is a sensitive indicator of aridity. In the channels gypsum is almost completely missing in the uppermost centimeters below the surface. Beneath the top layer, the gypcrete horizon starts abruptly. This observation was verified by digging a cross section over an entire, 1.5 m wide channel. While white, powdery gypsum occurred on both 'banks' of the channel very close to the surface, it was missing in the area of the channel itself. Therefore, we assume that episodically running water is soaking the sediments in the upper part of the channels and that by scouring processes gypsum is removed. During these episodes the entire soaked material is mobilised, reworked, and removed, leaving a gypsum crust with an eroded and polished upper part and with a relatively thick cover of reworked channel sediments.

These observations outline the specific geomorphologic processes responsible for recent to Holocene evolution of the plain. Heavy episodic rainfalls cause water discharge (surface wash) on the desert plain. The flow is almost always unsteady in time and non-uniform in space; it is characterized by high sediment yields. The most important process involved is scouring or entrainment. The depth of scouring is indicated by the thickness of the gypsum-free top layer. The almost ubiquitous top layer is moved by the scouring processes of the ephemeral flows on the surface. Even the cobbles of the desert pavement are reworked and transported. These processes also explain the distribution of angular clasts and course gritty sand that is confined to the surface right next to the rocky outcrops.

A mechanism that acts towards a levelling of existing differences in relief is characteristic for the Namib plain. The fabric of Section D illustrates this quite well. The section is located at the foot of a long gentle slope. First, the section was a granite outcrop that towered the plain. Mechanical weathering caused exfoliation of the granite. Then the gaps between the different exfoliation sheets were filled with red eolian sand that was finally indurated by carbonate. These subaerial processes terminated when the granite was slowly buried by encroaching material due to surface wash. Gypcrete formation began. Presently, the inclined gypsum crusts are capped by the top layer.

Based on our studies of gypcrete sections in the central Namib plain we suggest that the study area is affected only by planation processes but not by denudation processes. Because of the inclination of the Namib plain of about 1° and because of the great extent of the Namib plain from the Atlantic coast in the west to the Great Escarpment in the east, the transported material of the gypsum-free top layer (thickness: a few centimeters) does not contribute to a denudation of the desert's surface. On an average, the transport work remains the same at every place of the Namib plain, thus resulting in a value of denudation of 'zero' (comp. Rohdenburg 1989:21). Although surface wash occurs episodically, no active denudation exists. These results are corroborated by the following facts: (1) The observed different altitudes in which the Miocene calcretes are located; (2) The preservation of the Miocene calcretes and their relation to the Namib Unconformity Surface; (3) The old age of the gypcretes; and (4) the rapid dissolution of gypsum under humid conditions.

Our research on the Namib gypcretes points to their relationship to fog precipitation and surface and channel development. It generally infers their formation due to soil development during periods of aridity with insufficient soil water to dissolve the gypsum crystals. Due to the lack of dates derived directly from sediments and soils of the Namib plains, the gypcretes cannot make a direct and chronologically controlled contribution to our understanding of the Namib environmental change. However, more rigorous data have been obtained from fluvial, lacustrine, and cave features (Kuiseb valley, vleis of the northern Namib Sand Sea, Rössing and Tinkas caves) of areas adjacent to the central Namib gravel plain. Yet, paleoclimatic interpretation of this extensive collection of data associated with the Namib Desert and controlled by more than 100 ^{14}C dates, a couple of U/Th and TL age determinations, remains ambiguous. The ^{14}C dates from calcretes and lacustrine calcareous sediments seem too young. The same applies to the speleothem ^{14}C ages from the Namib caves. The Kuiseb valley sediments (especially the Homeb Silts) document the paleoenvironmental conditions of the upper reaches of the river and not those of the hyperarid desert. Therefore, the paleoclimatic information from the gypcretes of the central Namib gives important additional evidence for the climate history. Soil development depends on climate, parent material, relief, vegetation and animals, time, and human cultivation practises. In the central Namib Desert the factors 'climate' and 'time' are the most important ones.

Based on our investigations of the gypcrete profiles we can distinguish between different climato-geomorphic phases. The erosional surface of the central Namib gravel plain north of Gobabeb is roughly identical with the Namib Unconformity Surface (NUS) which is covered by calcretes of Miocene age south of the Kuiseb and in some places east of our study area. The occurrence of calcretes or remnants of calcretes, at the lower parts of the gypcrete profiles topping the (decomposed) bedrock proves that the End Miocene calcretes developed more or less all over the NUS. Moreover, these calcrete remnants document that since End Miocene times no or little denudation of the NUS occurred. Erosion processes are confined to the incision areas of the Kuiseb and Swakop Rivers (gramadulla relief) (see Ward 1987). Since there are neither erosional nor accumulation features on the central Namib plain, the time between the End Miocene with calcrete formation and today is represented only by the gypcretes. The gypsum soils show that the area was not affected by humid phases during the last ca. 5 million years. There is evidence that a gritty granite desert sediment overlies these calcretes separating the calcretes from a 4 cm thick layer of eolian sands.

The sands with red and pink colour (5-7,5 YR) originate in the Namib Sand Sea. They can be related to a more windy climatic phase (reactivation of the Namib Erg, see Besler 1981, 1991). The sedimentation of the Oswater Conglomerate Formation may be correlated with this phase, too; the coarse gravels show intercalations of arenite dated to 900 ka BP (Ward 1988). After deposition the sand layer was cemented by carbonate. This process may not indicate a moister climate because enrichment of carbonate takes place even under modern arid conditions. Eitel (1993, 1994) describes calcrete formation as result of $CaCO_3$ input by dust over long periods and Marion (1989) emphasizes that the rates of $CaCO_3$ formation in desert soils are highly variable and potentially useful in estimating the age of the soil profiles. Considering the extremely low intensity of pedogenic processes and the sensitivity of gypsum crusts to erosion and dissolution during conditions of higher moisture supply, allows a paleoclimatic interpretation: Gypcrete formation processes start in the Early Pleistocene and do not support evidence of moist phases during this period. Studies in adjacent areas confirm these results: Speleothems of the central Namib Desert (Rössing and Tinkas Cave) have been dated and the results suggest that pluvial phases did not occur since ca. 25 ka BP (Heine & Geyh 1984, Heine 1992). Although there are some methodological problems in dating the speleothems (Geyh 1995, Heine in press), it is most likely that there were no major shifts in moisture since at least 100 ka BP ($\delta^{18}O$-Stage 5). Other results, such as paleopedological studies at the desert's margin in the valley of the Tsauchab river and sedimentological and paleopedological findings in the Sossus Vlei area confirm uninterrupted aridity since at least 25 ka BP (Heine 1991, 1992, 1993). Palynological investigations of terrestrial (Sossus Vlei) and marine sediments off the central Namib (Caratini & Tissot 1982, van Zinderen Bakker 1984, van Zinderen Bakker & Müller 1987) also point to an arid Late Quaternary climate without major hygric fluctuations. There are no Late Quaternary phases that can be compared to and correlated with the pluvials in northern Africa. The Quaternary climate of the central Namib and the adjacent desert areas is characterized by persistent aridity. There is some evidence for a few moister periods of minor significance prior to 100 ka BP. Paleopedological, palynological, and karst-morphological studies document relatively moist phases only for the Tertiary.

If we assume that the sand layer of the presented gypcrete profiles has an age of ca. 900 ka BP (like the Oswater Conglomerate Formation) and that the cementation of this sandy layer requires 50,000 to 100,000 years – which seems to be realistic when compared to the soils on the 10 ka Kuiseb terraces – then the gypcretes formed during a period of roughly 800,000 years. There is no evidence documented by the gypcrete profiles that major climatic changes influenced the development of the sections. Therefore, we conclude that the climatic conditions of the central Namib plain prevailed more or less unchanged during the Brunhes epoch. These observations are corroborated by results presented by Heine (1990): The influence of orbital parameters on climate changes is documented by climatic-sensitive facies of marine and terrestrial origin ($\delta^{18}O$, global ice-volume, and global climate fluctuations); however, the long-term evolution of the Namib landforms does not seem to reflect this climatic history with the obvious frequency cycles. Rather, the landforms of the Namib point to phases during which adjustment occur to the different periods (e.g. the past 700-900 ka with 100,000 year cycles) and to phases during which the climatic setting is represented by the landforms (characteristic desert forms) (Heine 1990).

Our field-based age-related criteria were established on the basis of the degree of gypcrete development, the stage of gypsum accumulation, and characteristics of the gypcrete soil horizons (texture, structure, colour, mineralogy etc.) together with sedimentological observations. The interpretation of gypcrete soils and their paleoclimatic implications as presented in this study contribute to the understanding of the climatic and morphologic history of the central Namib Desert. It becomes more and more evident that the climatic evolution of northern and southern African deserts was different during and since the Late Quaternary (Hövermann 1988, Heine 1991, Brook et al 1990, Partridge 1993).

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