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Climate, weathering, crust formation, dunes, and fluvial features of the Central Namib Desert, near Gobabeb, South West Africa

by
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ABSTRACT

The central Namib Desert inland from Walvis Bay, South West Africa, has a rainfall of 23 mm and a fog precipitation of 31 mm per annum at Gobabeb. The temperature range is only 6,5°C in a year. The basic rock types of the area are Damaran schists, marbles, quartzites and Salem granites. The rocks, particularly the granites, have been intensely weathered by the various arid weathering processes into tafonis, honeycombs, exfoliated scales, and constituent grains. Marbles show minor solution forms, including 'rillen'. The processes responsible for the weathering are discussed, and reference is made to the role of salt crystallisation, fog, lichens, and insolation. Data on soil and rock temperature fluctuations are presented. The central Namib is also covered by gypsum crusts, calcrete and desert pavement. In a calcareo-gypsiferous crust at Gobabeb some 20 m diameter polygons have developed, but their origin is uncertain. They are situated on a terrace at 42 m above the Kuiseb River. The Kuiseb also has two lower terraces, at 20 and 6 m above its present bed, and a marked convex long profile. It forms the northern limit of the Namib dune-field, which consists of linear ridges, largely unvegetated, and having a height of 80-100 m. Some wind data are presented which show that strong, infrequent easterly winds are a major factor in their north to south orientation. The paper ends with a discussion of erosion surfaces and the evidence for Quaternary climatic change in the area.

INTRODUCTION

The Namib Desert, the west coast arid zone of Southern Africa, extends from the drier parts of the winter rainfall zone of the Western Cape Province to just north of Moçamedes in Angola. Wellington (1955) places the southern boundary in the vicinity of the lower course of the Olifants River and remarks that the arid surface and extensive areas of moving sand continue to the Baia dos Elefantes (13° 10′ S). The desert extends laterally to the foot of the Great Escarpment, generally a distance of 80-140 km, though towards the north it narrows considerably — 75 km near the mouth of the Cunene and only 11 km near Moçamedes. The desert rises to about 900 m at the foot of the Escarpment.

DIVISIONS OF THE NAMIB

Various attempts have been made to sub-divide the Namib. Wellington (1955) called the southern part, as far north as the Luderitz-Aus horst, the **Transitional Namib**. North of this area, towards the Kuiseb River, he calls the **Middle Namib**. It is a tract of country with a longitudinal extent of up to 140 km. and a latitudinal extent of around 400 km. North of the dune area is the **Damara** or **Northern Namib**. Except in the coastal belt between the Kuiseb and Swakop Rivers it is relatively free of sand. Within the Southern Namib the great German geologist, Kaiser, attempted a geomorphic division into the **Trough** (**Wannen-**) **Namib**, where alternating soft and hard strata have been scoured by the wind, the **Plain** (**Flächen-**) **Namib**, where the sand has been deposited in the more sheltered localities to form flat surfaces, and the **Dune Namib** of isolated barchans and linear chains. Logan (1960) on the other hand, divided the central parts of the Namib (around Walvis Bay) into the **Coastal Namib**, where direct maritime effects are felt, the **Namib Platform,** and the **Dune Namib.** Spreitzer (1966) divides the same area longitudinally between the **Exterior** or **Coastal Namib**, the **Interior Namib**, and the **Anterior Namib** (the eastern transitional zone).

Basically, this report deals with the geomorphology of the northern part of the Dune Namib and the southern part of the plains, which stretch, with but little sand cover, north of the Kuiseb River (Figure 1). Most of the field work was done at the Namib Desert Research Station at Gobabeb, which is about 100 km south east of Walvis Bay on the Kuiseb River. Indeed, the area in question is that covered by N.A.S.A. Gemini V Colour satellite photograph S-65-45578 (N.A.S.A. 1967). The photo shows the abrupt division along the Kuiseb between the dune area and the rock plains to the north, and the presence of massive inselbergs detached from the Great Escarpment which forms the eastern boundary of the area of study. The photo also shows the difference between the coastal and inland dunes, the somewhat disrupted dunes between the Tsondab Vlei and the sea, and the formation of coastal spits and pans. The white marble ridges of Swartbank and the area to the north also show up particularly well on the satellite photo. Examination of Satellite photo S-65-45580 brings out the contrast between the heavily dissected country to the east of the Great Escarpment and the relatively flat plains of the Namib itself.

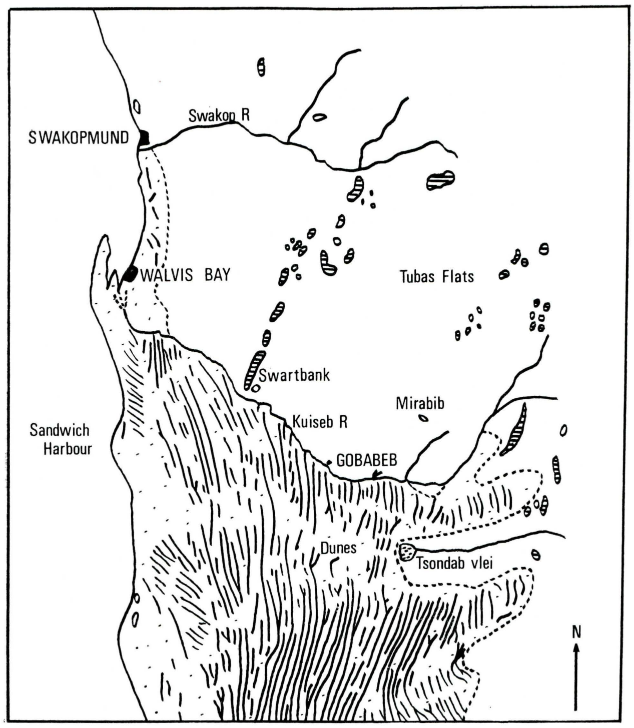

Figure 1. The Central Namib Desert near Gobabeb.

THE GEOLOGY OF THE CENTRAL NAMIB

Recently the terminology and dating of the more ancient rocks of South West Africa have undergone great change. The works of Smith (1962), Martin (1965a, 1965b), and Clifford (1967) show the present position.

Basically, the Namib Platform in the area is underlain by late Proteorzoic rocks of the Damara System, including the Khomas schists of the Swakop facies. Intruded into these are the Salem Granites of Post-Damara times — granites which outcrop in the immediate vicinity of Gobabeb. They are generally grey porphyritic biotite granites, containing often large pheocrysts of orthoclase and microline felspar. The Damaran metamorphics are highly variable, and include mica schists, marble, granitic gneiss, and quartzite.

Among younger intrusive rocks are black dolerite dykes. These usually show up clearly as linear ridges on air photographs, though sometimes larger masses, as along the lower Swakop valley, form small inselbergs.

The other major group of rocks consists of a variety of superficial deposits, including gypcrete and calcrete. These are discussed in a later section.

Clifford has dated rocks of the Damaran orogenic episode by isotopic methods and has found most of them to be between 500 and 550 million years old.

CLIMATIC BACKGROUND

It is not possible here to discuss the climatic conditions of the Central Namib in detail. This has already been done completely by Logan (1960) and Schulz (1969). However, the opening of the first-order weather station at Gobabeb in 1962, and the paramount importance of climatic conditions for the geomorphology, require some discussion.

The rainfall of the Central Namib is very slight. The average annual total for the period 1962-1967 at Gobabeb was only 23 mm. Since 1899 the rainfall at Swakopmund has averaged 14 mm. This compares with about 15 mm for Luderitz, in the southern Namib, and is similar to that for various other coastal deserts. Port Etienne (Mauretania) has 35 mm, Aden has 45 mm, and El Refugio (Baja California) has 62 mm (Meigs, 1966). The rainfall in the Atacama is perhaps very slightly lower, with 1 mm being given as the mean annual rainfall of both Africa and Iquique. The rainfall increases steadily towards the Great Escarpment.

In common with certain other desert areas, rainfall can be of great variability and of occasional great intensity. The highest daily total so far recorded at Gobabeb is 16,5 mm, but 22 mm have been recorded in a day at Goanikontes (on the Swakop River), and 88 mm at the inland station of Donkerhuk. In 1934, 153 mm of rain fell at Swakopmund. However, it is probable that on the coast daily intensities never reach the same heights as further inland, and at Walvis Bay and Luderitz maximum daily totals recorded up to 1944 were 15 and 9 mm respectively (Meteorological Handbook, 1944). Nevertheless, the geomorphic significance of events of high magnitude but low frequency does not need stressing for an arid environment. Stengel (1964), for instance, has shown that the flood of 1934 at Swakopmund transported 35 000 000 m^3 of sediment down the Swakop River advancing the coastline more than 1 km into the Atlantic.

A further component of the precipitation not so far considered is fog. These are very frequent and extend about 110 km inland. The fogs do not have the same duration as those at Port Nolloth in the Republic of South Africa (Meteorological Handbook, 1944), but even at Gobabeb, in spite of its distance inland, fog was present at the station itself or in the neighbourhood on an average of 102 days *per annum* over the period 1964-1967 inclusive. Whilst the fog only precipitated on an average of 60 days in the year, this produced a precipitation of 31 mm *per annum,* a figure slightly higher than the rainfall itself. Boss (quoted by Eriksson, 1958) estimated the yearly fog precipitation at Swakopmund to be 35-45 mm, compared with 20 mm at 40 km inland. Daily quantities are small, though 6,5 mm have been recorded in one day at Gobabeb. Thus the fogs bring a significant quantity of moisture into the desert, and this combined with its chemical constituents is of considerable ecological and geomorphic significance.

The winds in the Central Namib are another very important part of the desert environment. The wind data in Figures 2 and 3 give an idea of the annual variability of the winds. At Gobabeb, east and south winds are at a maximum frequency in winter and have mean velocities up to 21 km/hour, though actual velocities may exceed 50 km/hour. Winds from the north west show their highest frequency in summer but have consistently lower velocities. In January diurnal variation is slight, but in the winter (July) the direction is south easterly at night until about 1000 hours when it starts backing round the clock, becoming south easterly again at midnight.

The winds in the Central Namib do not appear to be as potent as those in the southern Namib. Wind velocities reach their maximum off the southern part of the coast of South West Africa, and at Gobabeb the southerly winds do not maintain that steady and violent blast during the day which characterises the southern Namib. At Luderitz the average force is about Beaufort 6, and gales are common, but at Walvis Bay winds of force 8 are rare, and velocities are lower still inland. Merensky described the winds of Luderitzland thus: "During the greater part of the year hurricane winds blow from the South and keep the sand dunes constantly shifting. At times this wind is so boisterous that sand-grains of pin-head size are hurled through the air above the ground, whilst gravel as large as beans is transported along the surface." The greater variability of direction, combined with lower velocities, makes the Central Namib a very different sort of geomorphic environment to that at Luderitz.

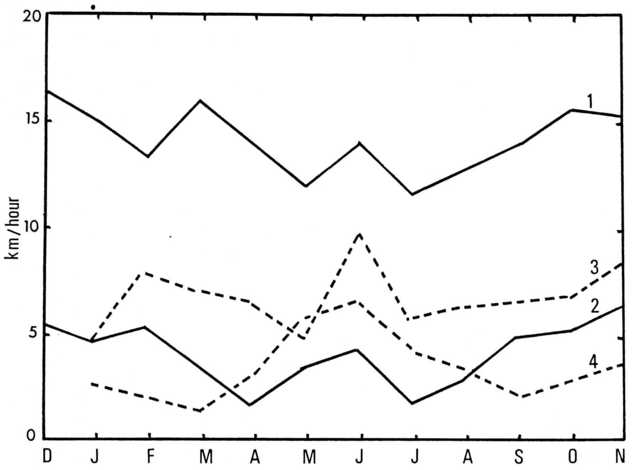

Figure 2. Mean wind velocities for Gobabeb and Walvis Bay, December 1965 to November 1966. 1 = Walvis Bay, 1400 hours; 2 = Walvis Bay, 0800 hours; 3 = Gobabeb 1400 hours; 4 = Gobabeb 0800 hours.

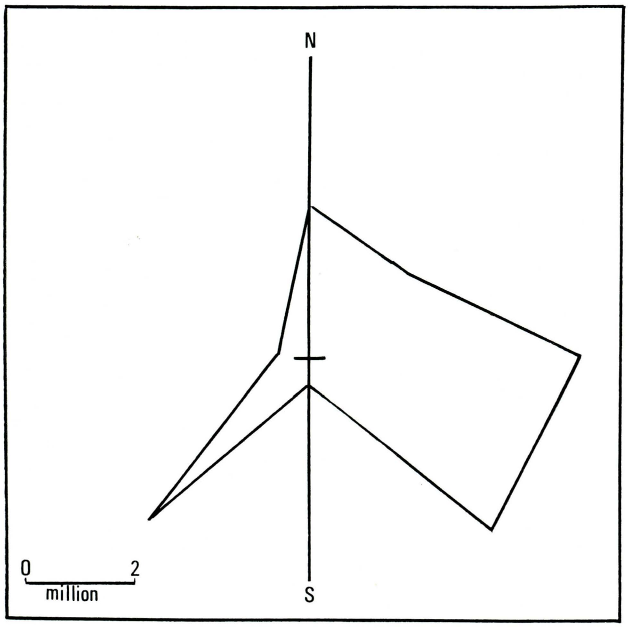

Figure 3. Wind rose for Gobabeb to show sand moving power of winds of each of eight directions. Each axis represents the cube of the velocity of all winds greater in speed than 20 km//hr, multiplied by their frequency in hours per year.

The last aspect of the climatic background is that of temperature. The whole of the coastal Namib shows a remarkable similarity in average monthly and yearly temperatures (Table 1). The temperature ranges are also small, with the mean annual range between warmest and coldest months being 9°C at both Walvis Bay and Swakopmund. At Gobabeb the mean March temperature is 24.2 compared with 17,7 for July, an annual range of only 6,5°C. The average daily aperiodic range (mean maximum less mean minimum) is of the order of 16-18,5°C throughout the year at Gobabeb. Frost is almost unknown in

Table 1. Mean monthly temperatures (°C).

	Walvis*	Luderitz*	Gobabeb +
J	19,05	19,00	22,20
F	19,50	19,50	22,10
M	18,94	19,66	24,20
A	18,38	18,27	22,20
M	17,16	16,77	21,80
J	16,11	16,00	18,10
J	14,66	15,22	17,70
A	13,83	15,22	17,90
S	13,94	14,77	18,90
O	15,16	15,61	19,30
N	16,72	16,90	20,30
D	18,05	18,27	21,30

	Africa²	Port Etienne²
J	22,22	19,44
F	22,22	20,00
M	22,22	20,55
A	20,00	21,11
M	17,77	21,66
J	17,22	22,77
J	16,11	23,88
A	16,11	26,11
S	17,22	23,88
O	17,77	22,77
N	18,88	19,44
D	21,11	21,66

Sources:

* Handbook, 1944

\+ Records at NDRS, Gobabeb

² Meigs

the coastal tract, though, at the other extreme temperatures of over 40°C have been recorded on occasions, generally in association with strong easterly 'berg' winds. In some deserts maxima may be rather higher, and in general the Namib does not suffer from any very great extremes of temperature over short periods. This fact may be of some significance in terms of rock weathering.

ROCK WEATHERING IN THE NAMIB

The weathering of rocks under conditions of very low rainfall has been a major theme in arid geomorphology, with much of the best work having been undertaken by German scientists. Some of the early work was summarised in Walther's classic reviews (1891, 1900), and there is no doubt that material from the Namib played a part in the formulation of his views. Certainly the Namib shows many very beautiful weathering forms on both a large and a small scale, and most types can be seen within a short distance of Gobabeb. A series of photographs illustrates the more common varieties.

At Gobabeb the Salem granite, a grey biotite porphyritic granite, containing many inclusions of orthoclase phenocrysts, and large amounts of pegmatite, displays honeycombing, case-hardening, exfoliation, tafoni formation, and granular disintegration.

The honeycombs are small pits in the rock, generally about 30 mm in diameter and up to 15 mm deep. They show no marked orientation, suggesting that wind action is unimportant in their formation, and appear in large clusters. On some boulders they clearly result from the weathering out of phenocrysts, but this is not always the case.

Case-hardening, which includes the slight cementation of rock so that it presents more resistant and upstanding surfaces, is particularly well-developed along joints in the granite, a rock type to which it seems to be restricted. Sometimes the case-hardening is little more than a brown stain.

Exfoliation, the spalling off of sheets of rock parallel to the rock surface, is linked with the presence of the rounded granite bosses and boulders at Gobabeb. Whilst sheets as much as 200 mm thick may spall off, they are frequently much thinner. At Mirabib, inselberg sheeting has developed on the granite core.

Perhaps the most dramatic of all the granitic weathering forms at Gobabeb are the tafonis, cavernous hollows with interiors of larger dimensions than the exterior orifices. Typically they have internal measurements 80 cm across as against entrances with diameters of 20 cm. Such features also occur in granite south of the Brandberg Mountain. There are large numbers of reports of tafoni in the literature from other parts of the world. The type-site is Corsica, whence the name is derived (Reusch, 1882; Tuckett and Bonney, 1904). They are particularly common in granitic rocks, and are well-developed in Antarctica (Prebble, 1967), Elba, Aruba, Peru, north west India, and the deserts of Central Asia (Wilhelmy, 1964).

Finally, much of the granitic debris has broken down into its constituent grain sizes by a process of granular disintegration to give 'gruss'.

These various forms, though best developed in the granites at Gobabeb, Rooikop and Mirabib, do also occur in schistose rocks. Dolerite, on the other hand, tends to show different weathering characteristics from the other rock types. Generally it has a black or dark red brown patina, and it tends to break down into large boulders and cobbles. In this it is different from many other rock types which show a rather more abrupt break-down into constituent grains. The tendency for basic rocks to behave like this in arid lands was noted in the American deserts by Bryan. No exfoliation, tafonisation, or honeycombing was noted on the dolerite, though anvil-shaped remnants were reasonably common.

Marble, well exposed at Swartbank, and extending northwards across the Tubas Flats in the form of ridges, shows some small-scale solutional forms, though nothing akin to the larger solutional forms of more humid lands was noted. Rillen on the marble at Swartbank are illustrated in the photo, though in addition to the rillen there were small pock marks and brown staining. That the marble had undergone some solution is evidenced by the relatively high calcium carbonate contents of the gypsum crusts developed on and around the Swartbank inselberg. This is discussed further in the section on the crusts of the Namib. In places the surface of the gypsum crust itself shows minor weathering to give vermiculations — pitted and ridged micro-relief.

Weathering factors

Traditionally, the physical weathering caused by temperature alterations was thought to be of major importance in deserts. This process was termed 'insolation' by Walther, and his ideas on its effectiveness rapidly became widely applied in Egypt, Sinai and elsewhere. Grotefeld, an early worker in the Namib (quoted by Calvert, 1916) spoke of "Enormous masses of sand, due to the sudden and violent changes of temperature acting upon granite, gneiss and similar primitive rocks. It is said that on a cold night, following a hot day, the splitting of the rocks sounds like the rattle of musketry". Later workers put forward evidence of insolation weathering in the Namib, and Kaiser (1926), for example, suggested that the disintegration of quartz in the Nama Formation was due to this cause (p. 233-4) though he recognised that some split granite boulders (kernsprünge) were caused by the cooling effect of a rain downpour on hot rocks. Logan (1960), on the basis of fresh cleavage faces, continued to propose the mechanical disruption of rocks in the Central Namib, and Greenwood (1962) and

Ollier (1963) have recently supported insolation theories in Australia and the Middle East respectively.

The theory behind insolation weathering has been summed up thus by Hockmann and Kessler (1950): "Gradients in a granite structure resulting from the usual diurnal temperature changes cause internal stresses which, after numerous repetitions, cause a weakening effect on the stone. It also seems likely that the granite may be affected by the unequal expansion of the different mineral constituents, and the fact that the principal constituents, namely feldspar and quartz, expand unequally along different crystallographic 'axes'."

In general, however, current thought, as reviewed by Sparks (1960) and Schattner (1961) does not support the idea of insolation being a major cause of rock breakdown in deserts, and Walther himself (1924) later recognised a lack of evidence for the insolation process and replaced the term 'Insolation' by 'Zerspaltung' (splitting), a term which allows splitting effects besides solar heating. The change in attitude has resulted from the theoretical and experimental work of Blackwelder (1933) and Griggs (1936) and from the field work of Roth (1965).

However, one must mention that the experimental work so far conducted has not been able to reproduce the tensile stresses produced in large bodies of rock, and Griggs' methods of heating and cooling, together with his cycle times, seem highly suspect. Nevertheless, the temperature fluctations of the Namib are not particularly severe compared with those noted by Roth and others, though sand surface temperatures at Gobabeb in 1965 showed a maximum diurnal range of about 50°C and a maximum annual range of 70,5°C. The temperature variation, both annual and diurnal, falls off very rapidly beneath a thin cover of superficial material (Figure 4) and the temperature fluctuations beneath different thicknesses of granite slabs resting on sand at Gobabeb are shown in Figure 5. The steep temperature gradients through a rock mass, resulting from the low heat conductivities of rocks, has often been seen as a cause of the splitting off of thin silvers of rock from boulders.

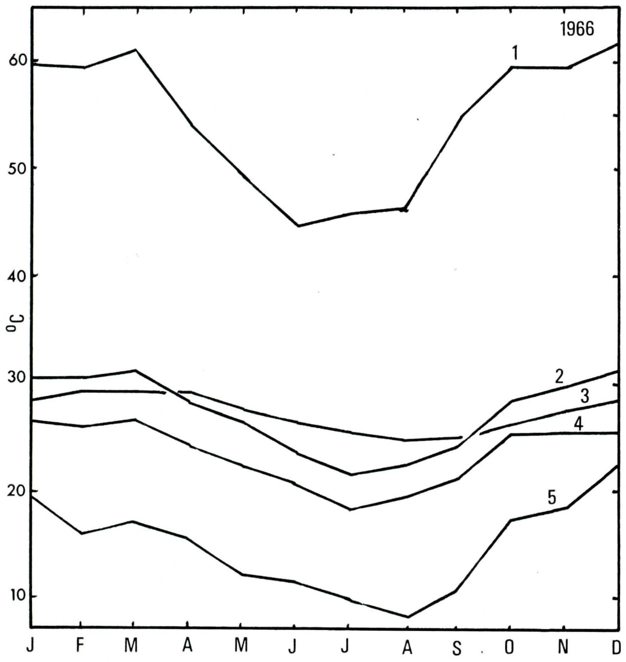

Figure 4. Soil temperature fluctuations at Gobabeb. 1 = Surface at 1400 hours; 2 = 30 cm at 0800 hours; 3 = 120 cm at 0800 hours; 4 = 10 cm at 0800 hours; 5 = Surface at 0800 hours.

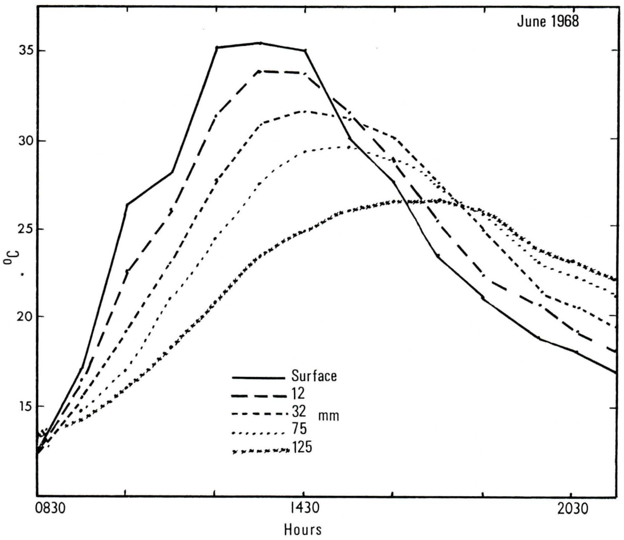

Figure 5. Rock temperature variations beneath granite slabs at Gobabeb.

However, it has now been recognised that there are a large number of other weathering mechanisms in deserts, and that exfoliation can result from such factors as hydration, the initial presence of cores surrounded by weaker zones resulting from the way the magma solidified, or from pressure release following the exposure of rocks at the surface by erosion. Also, Hockmann and Kessler's experimental work showed that granite suffered from expansion effects caused simply by wetting.

An alternative factor involved in rock weathering in the Namib, and one which could lead to the production of fresh cleavage faces, is salt weathering. This takes place either through salt crystallisation, thermal expansion of the salt, or salt hydration (Cooke and Smalley, 1968). Wellman and Wilson (1965) describe salt crystallisation as "A powerful undercutting agent that constantly tends to steepen slopes to the limit of rock strength and is responsible for . . . . cavernous weathering, coastal and desert platforms, some kinds of tors and at least some hills that have been described as inselbergs". Granite seems to respond particularly well to its effects, and Birot (1968) showed that when crystals of sodium sulphate and sodium carbonate develop pressures of 240 atmospheres and 300 atmospheres respectively granite is completely shattered in four months by daily moistening of a saline crust. He concluded, "In nature, this wetting would be the result of mists and light showers which are more frequent in deserts than might be expected."

In the Namib, fogs, as already pointed out, are of very frequent occurrence, and such analyses as are available, though they need to be accepted with some caution, suggest a remarkably high salt content of the fog. Eriksson (1958) using Boss's data for Swakopmund, proposed a yearly precipitation of atmospherically derived salts of 120 kg/ha, which compares with a value of 130 kg/ha found for the Israeli coastal tract (Eriksson and Khunakasem, 1969). Four analyses of fog water from Walvis Bay, Rooibank (2) and Gobabeb showed total dissolved solids at 180°C of 9860, 1290, 795, and 1175 respectively, (Koch, pers. comm., 1967) whilst my own observations of fog water drips and precipitation in the self-recording fog gauge at Gobabeb during May and June 1968 showed electrical conductivity readings equivalent to a range from 100 to 1000 parts per million. All samples were alkaline. Sulphate was a major component of the fog water, and this is known from experimental work to be one of the most effective agents of rock breakdown when present as either sodium sulphate or magnesium sulphate (Goudie, Cooke and Evans, 1970).

The appreciable frequency of application of a thin spray of salt-rich water by the fog, followed by rapid evaporation by sun and wind, gives natural conditions in the Namib which correspond remarkably well to the laboratory conditions employed by Birot (1954). Moreover, the Central Namib is very rich in gypsum and saline crusts, and dust from these would contribute salts by direct deposition on surfaces and in cracks. In addition to salt weathering this could also promote what Ollier (1965) has termed 'dirt-cracking'.

The crusts may themselves be of some importance in breaking up underlying rocks. Soil pits dug by the author where gypsum overlies granite shows how the gypsum penetrates the granite and breaks it up. At Gobabeb small weathered bosses are being exhumed from beneath the crust by incision of small drainage lines. Road workings on basalt outcrops inland from Swakopmund show that gypsum veins have penetrated and split the basalt to a depth of over 20 feet. Around Mirabib, surface limestone (calcrete) is breaking up underlying schists, whilst on the top of Swartbank a gypsum/carbonate crust is breaking up the marble.

Chemical weathering is evidenced in the Namib in the form of 'rillen' and staining on marble, stainings and patinas on other types of rock, case-hardening on granite, and the formation of an 'iron hat' on a dyke of ultra basic dunite in the Kuiseb area. Kaiser (1923), in a pioneer study, showed the presence of kaolinisation near Luderitz. Thus whilst chemical weathering may not have the quantitative importance it has in more humid lands, it is not by any means absent. On the dolerites the lichens probably play on important role, for as Lowdermilk has suggested in America, lichens assist in the mobilisation and deposition of manganese and iron to give 'desert varnish'. It has also been recognised that blue-green soil algae, such as one finds beneath translucent pebbles in the Namib, may play a similar role. At Swartbank, lichens of such species as *Caloplaca elegantissima* and *Parmelia hottentotta* (Giess, 1962) cover a large amount of dolerite, and removal of the lichens generally shows the attachment of small grains of rock to them, and also the pitting of the surface beneath. Oborn (1960) mentions that the iron content of lichens is on average 5,16 mgm per gm of dry matter, compared with an average of only 0,30 mgm per gm dry matter for most land plants. Lichens are also present in large quantities on some marbles at Swartbank, and the probable importance of lichens in the weathering of limestones in deserts has recently been discussed by Krumbein (1969).

It is also possible that the salts may have a chemical role in the weathering in addition to their physical role described so far. Coleman, Gagliano and Smith (1966) have suggested that the pH of a concentrated salt solution is high, and that just prior to complete drying a thin film of brine will cover the rock material and be in contact with atmospheric oxygen, so that oxidisation potential will be high.

THE CRUSTS OF THE NAMIB

One of the most striking features of the Central Namib plains and river terraces is the widespread nature of various types of crust. There are basically two types: gypsum crusts (gypcrete) and calcium carbonate crusts (calcrete). Locally the gypsum crust reaches 4 m in thickness (Martin, 1963). In reality, however, with the exception of high-grade deposits which contain as much as 90% pure gypsum, most of the gypsum crusts contain moderate amounts of impurities, of which calcium carbonate is a major one. Martin (1963) describes the location of some of the higher-grade deposits, and believes that the gypsum crust results from the alteration of an older and underlying calcrete by marine hydrogen sulphide eruptions. Whether such special causes are required to account for what is normally a common feature of dry maritime deserts, and also some interior deserts, the present author is not sure. In the vicinity of the marble ridges and inselbergs the gypsum contains above average quantities of $CaC0_3$, and three samples from Swartbank had $CaC0_3$ contents of 44,5, 21,6 and 35,1 per cent, thus showing the local effects of the highly calcareous marble (96 per cent $CaC0_3$). The mean calcium carbonate content of the most calcareous horizon in 25 localities sampled by myself between Walvis Bay and just beyond Gobabeb, and by Scholz (1963) between Walvis Bay and his station Namib 7, was 12 per cent.

No particularly marked change is evident in the composition and character of the crusts until one is about 60 to 70 km from the coast. At that distance the rather puffy gypsum crust is largely replaced by a more compact and dense calcrete, containing a large amount of brecciated material derived from the breakdown of underlying rocks. Initially it is particualrly well-developed in the small, shallow drainage lines running from inselbergs such as Mirabib, probably because of the local presence there at certain times of more soil moisture. These young calcretes are seldom more than a metre or so thick.

Distinct from this younger calcrete is the great calcified conglomerate which caps the older geological beds in the area of the Kuiseb and Swakop canyons. This deposit, which may have a thickness as great as 30 m, seems to pre-date the incision of the drainage, and may well be of Pliocene age, thus corresponding in age to the great Kalahari limestone deposit of the Kalk Plateau. The conglomerate caps the canyon to give a feature of marked geomorphic importance. Another major class of calcrete in the area is that forming the Pleistocene river terraces. In the area between the Khan and Swakop rivers Smith (1965) has described Upper Pleistocene calcreted terraces at 12 m above present drainage level. Such low calcareous terraces also line the Tubas.

Calcretes are very extensive elsewhere in southern Africa, extending in the east as far as the 500-600 mm isohyet, in the south as far as the Cape Flats, and in the north as far as Moçemedes and Barotseland. They typically contain about 79 per cent $CaCO_3$, with silica being the next largest constituent, and are thought to have a dominantly pedogenic origin.

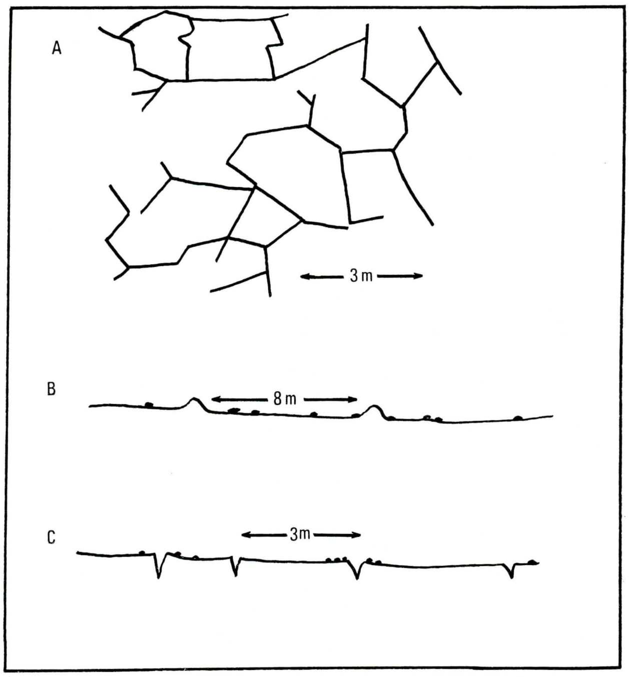

Figure 6. Diagrammatic representation of polygonal ground on Kuiseb Terrace crust at Gobabeb. A = Horizontal pattern of part of the area of polygonal structures; B = Cross-section of polygon with raised margins; C = Cross-section of polygons with fissure margins.

POLYGONS AND PATTERNED GROUND

One of the most interesting aspects of the weathered layer in the Central Namib is the presence of plentiful polygons in association with calcareo-gypsiferous crusts. Scholz (1963) has referred to a few small polygons on some river alluvium along the Soutrivier, north west of Gobabeb, and has illustrated that in Plate 47 of his thesis. Other small polygons (generally about 1 m or less in width) have been reported from gypsum in the Tibesti area of the Sahara (Meckelein, 1957) and have been found in a sandy, silty, salt duricrust near Abu Simbel, Egypt (Butzer and Hansen, 1968). They have also been described for salt in Death Valley by Hunt and Washburn (1960). Very large polygons are also known from the saline crusts of playa lakes in the western United States, where they have resulted from desiccation and contraction (Lang, 1943; Willden and Mabey, 1961; Christiansen, 1963; Neal, 1965; Neal and Motts, 1967). Some of these polygons may be as much as 300 m in diameter. Desert clay soil polygons and patterned ground are also well known, Alimen reporting them from North Africa (Alimen, 1953) and Ollier reporting them from South Australia (Ollier, 1966).

However, the best polygons at Gobabeb, which are developed on river terraces on the south side of the Kuiseb, seem to be much larger than any others reported for non-playa areas, and exhibit certain features not previously encountered (Figure 6).

Like most natural polygonal features, such as some tundra soils, columnar structures in basalt, and mud cracks, the columns are random orthogonal polygons (Lachenbruch, 1962), with a tendency towards hexagonal and pentagonal shapes. However, with the rather variable material in the Gobabeb crust the perfect hexagons do not always develop, though stripes or elongated polygons do not appear to be common. Some of the polygons have internal dimensions up to 20 m across, though between 8 and 9 m is the average size, and they show a variety of forms. The largest polygons have a raised margin of whiter calcareous gypcrete, with a calcium carbonate content of 25-40 per cent, and with a relief of as much as 40 cm. Other polygons may have very slightly raised middles, with pebbles forming rings around the dome, though this form is rare in its perfect form. A further class of polygon is marked not by ridges but by depressions along fissures, and they may or may not have upturned edges.

The polygons occur on the flat surface of the gypsum-calcrete terrace which lies at about 42 m above the south bank of the Kuiseb. The terrace extends well into the dune area. The crust is many feet deep, and with almost the whole terrace being cemented to a greater or lesser degree. The bulk of the cemented material is of sand size (see Figure 7), and is capped by, and contains some, well-rounded, wind-polished, fluvial pebbles.

Because of the minimal rainfall of the area it is difficult to attribute the polygons to setting and drying of the crust under present rainfall conditions, though infrequent storms of high intensity could conceivably have some effect. It is tempting to suggest a slightly higher rainfall in the past. The lack of fines in the polygon sediments seems to exclude any idea that they are formed either in playas or by expansion

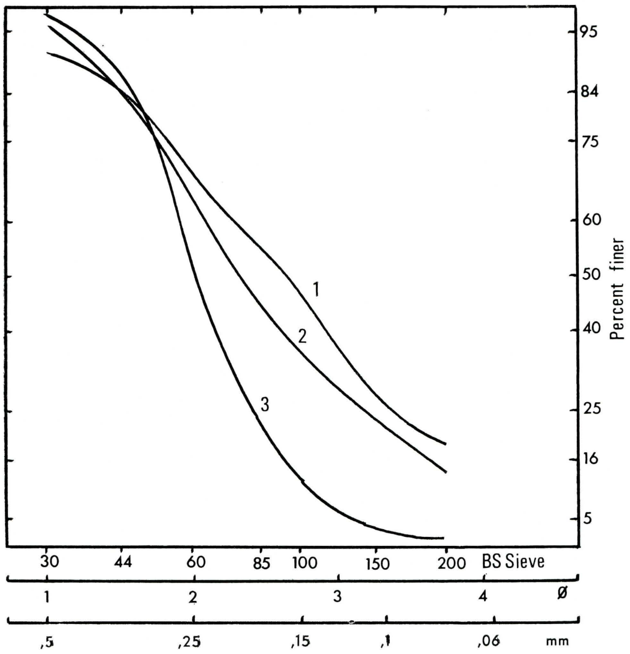

Figure 7. Particle sizes of polygonal ground material from Gobabeb (1 and 2) in comparison with Namib dune sand (mean of 14 samples) (3).

and contraction of clays. These have been the two favourite explanations for patterned arid ground in other lands. Any explanation through frost action, akin to that occurring in tundra environments, is ruled out by the almost complete absence of any frost. Evidence from elsewhere in South West Africa does not suggest a particularly cold period since the formation of the terrace, probably Upper Pleistocene, upon which the polygons rest. The raised nature and different material of some of the polygon rims preclude any explanation involving the stresses produced by the movement of massive 100 m dunes across the crust, though the results of such pressures have yet to be fully explored. Thus, unless there was some increase in humidity since the terrace was formed, it is difficult to explain the great size of the polygons (though the thickness of the crust may be one reason) or, indeed, the existence of the polygons at all.

The Kuiseb River

The Kuiseb River rises in the Khomas Hochland near Windhoek, and as a result of the relatively high rainfall and runoff in its upper catchment, is the first major river to reach the Atlantic north of the Orange. Even the Kuiseb, however, loses itself in a 'delta' inland from Walvis Bay. Within the Namib it has no south bank tributaries, though a few small north bank wadis, like the Soutrivier bring in some flow on rare occasions. Not all these gullies seem to have been able to adjust themselves to the incision of the Kuiseb, and so 'hang' above the main channel by a small amount.

Like other rivers of the north and central Namib, the long profile of the river Kuiseb shows a tendency towards convexity, rather than the concavity characteristic of most rivers, (see Figure 8, and Stengel, 1964, 1966). As Leopold, Wolman and Miller (1964) write: 'Rivers increase in size downstream as tributaries increase the contributing drainage area and thus the discharge. Concomitant with the downstream increases in the channel's width and depth and the general tendency for bed-particle size to decrease, the gradient generally flattens. In general the longitudinal profile is concave to the sky'. If, however, discharge does not increase downstream, as in the case of the Namib rivers, it is possible, if the other variables allow (load, size of debris, flow resistance, velocity, width, depth, etc.,) that the river will have an increased slope in its lower portions.

However, as Leopold *et al.* point out, even the Indus, Murray, Rio Grande and Nile, all of which have decreasing discharge downstream, show a tendency for concavity. It is probable that the very sharp decrease in discharge associated with the very marked climatic gradient of the Namib is responsible for this highly distinctive feature of the Namib rivers.

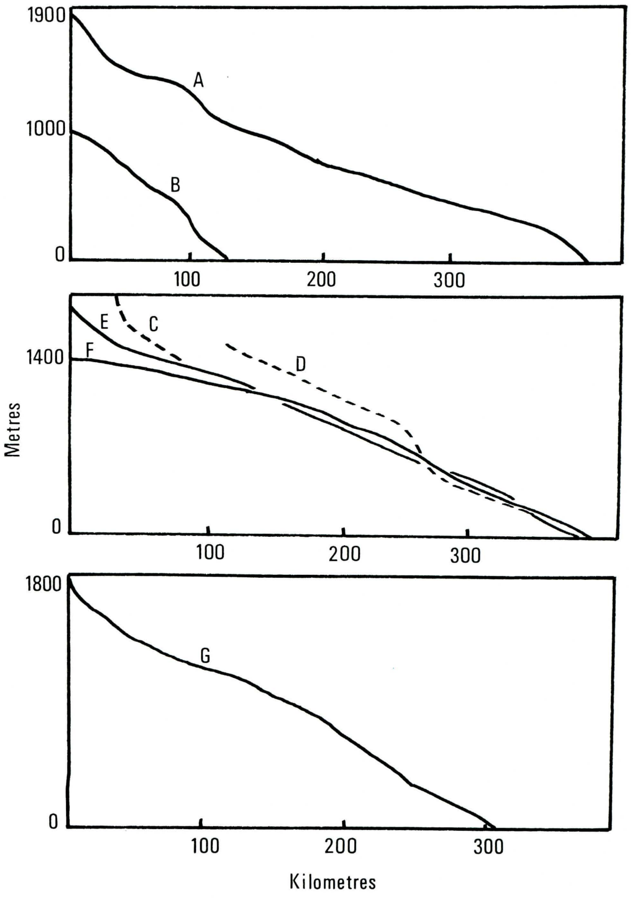

Figure 8. Longitudinal profiles of Namib Rivers (after Stengel, 1964, 1966). A = Kuiseb; B = Tubas; C = Klein Windhoek running into Swakop; D = Khan; E = Swakop; F = Ugab; G = Omaruru.

The Kuiseb has a mouth which shows evidence of a buried channel about 25-30 m below present channel level (Vegter, 1953). This indicates that there was once a lower base level associated with a lower still-stand of the sea. Evidence of higher sea-levels along the coast is also present in the form of raised beaches, a feature common to the whole western coast of southern Africa. Spreitzer (1966) reports a 14-16 m terrace at Swakopmund, with two possible lower terraces at 12 m and 4-6 m.

Alluvial terraces are present along the Kuiseb and are particularly well-marked around Gobabeb. The results of aneroid traverses by the author suggest the sequence of terraces shown in Figure 9. The best developed terrace is at about 42 m. Some of the lower terraces are cut into bedrock, generally granite and pegmatite, but all are capped by gypsum-calcrete crusts and rolled pebbles. The major dunes have developed on top of them. The crust is best developed on the higher terraces and has presumably played a role in the maintenance of the fresh, angular form of the terraces.

The dunes have in places invaded the river bed, but at no point except in the coastal tract have they crossed the river completely. The satellite photo shows the contrast well. It is possible that the Kuiseb has shifted its bed to the north under pressure from advancing dunes, and it has been suggested that the nature of rock bars in the sunken mouth and the flow of fresh water into Sandwich Bay support this. Largely fine-grained sediments have been banked up side tributaries of the Kuiseb near Ossewater, and are now being dissected. They are largely uncemented, and it seems possible that they formed in the not too distant past by the ponding up of the Kuiseb. The sediments are fine-grained, horizontally bedded, and in their upper layers a few well-preserved mollusca have been found. If they were of any great age one would suspect that they would have become cemented like the Upper Pleistocene terraces along the Kuiseb and other rivers.

There are various reasons why the dunes stop so abruptly at the Kuiseb:

1) Big dunes such as those at Gobabeb can only move very slowly, so that the almost annual floods which come down the Kuiseb past Gobabeb are able to remove the sand before it crosses the river bed. The Kuiseb floods have, however, only reached the Atlantic 15 times between 1837 and 1963 (Stengel, 1964). Thus, because of the drift of sand along the coast, the dunes cross the river in a narrow fringe by the sea, before being finally stopped by the Swakop River.
2) Rare northerly winds of high velocity would play a rôle in keeping the dunes from crossing the River.
3) In places a large volume of sand would be required to fill the river bed because of the depth of incision. This might require a considerable period of time.
4) It is possible that some dunes have only recently reached the river, and that the northern boundary of the dunes coincides with the Kuiseb purely fortuitously. There is some support for this idea from the eastern part of the dunefield, for maps in both Stapff (1887) and Range (1912) show a road or track running on the south side of the Kuiseb as far west as Natap.
5) The river, as mentioned earlier, may in places have shifted its course to the north under the influence of the advancing dunes.

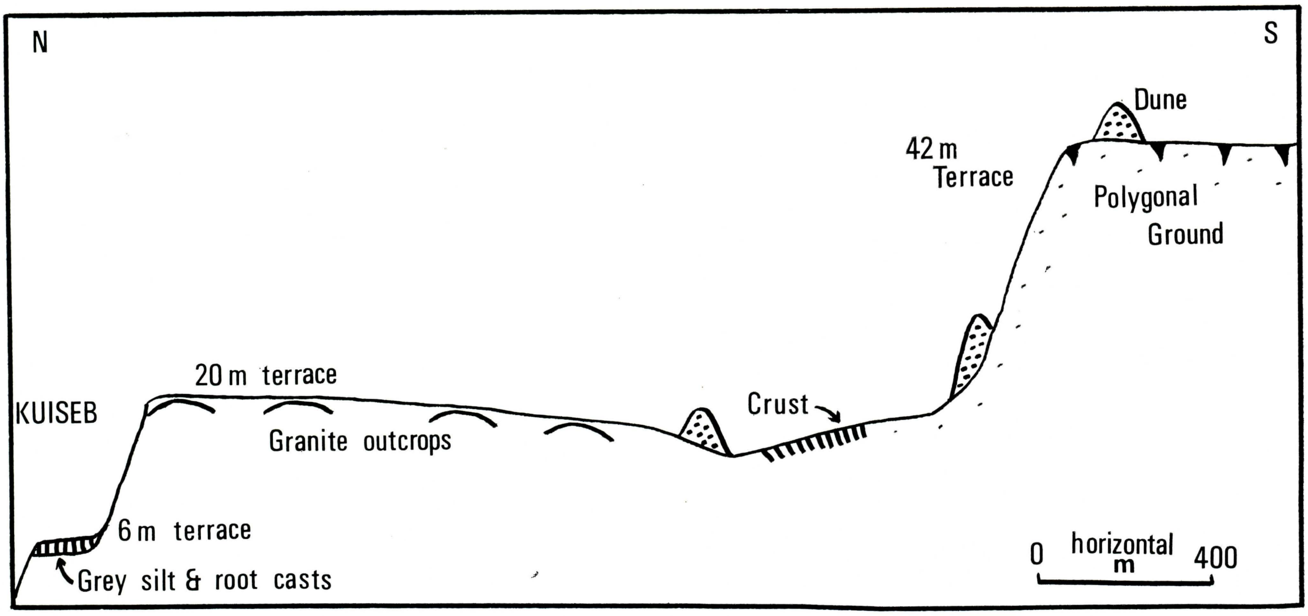

Figure 9. Diagrammatic representation of aneroid traverse across Kuiseb Terraces at Gobabeb.

THE DUNES OF THE NAMIB

The dunes of the Namib are possibly the biggest in the world, and examination of satellite photos by the astronauts of Gemini 4 and 5 suggests a broad similarity with those of the Empty Quarter of Arabia (N.A.S.A., 1967, p. 23, 47 and 137), and with those of southern Algeria (p. 154). They are basically linear dunes averaging near Gobabeb 80-100 m in height. Near the Sossus Vlei they have been reported as reaching 250 or 275 m in height above the surrounding plain (Jaeger, 1939, p. 19), which compares with recorded surveyed heights of up to 200 m from Arabia (Holm, 1960) and rather more from southern Iran (Gabriel, 1938). It is rather surprising, therefore, that these dunes have received so little attention in the literature (Stapff, 1887; Logan, 1960; Hoyt, 1966).

The main trend of the dunes is approximately from north to south, and it is probable that easterly winds of high velocity are a major factor in this trend, as they are dominant at velocities above the threshold required for the movement of sand. Nearer the coast, as the satellite photo shows, some dunes trend approximately north east to south west, and this probably result from the relatively higher velocities nearer the coast which enable the very frequent south westerly winds to play a greater rôle in sand movement. The nature of the winds at Gobabeb is shown in Figures 2 and 3, and Table 2.

Random measurements of 50 maximum dune slope angles show the average lee slope to be just under 32°, and the average windward slope to be 25°. They are larger than those of the interior sandveld of southern Africa — the Kalahari. In the Kalahari many of the dunes are degraded forms resulting from a wetter period since their formation, and have heights of 25 m or less. Only the 'alab' dunes of northern Botswana, with wavelengths of 1,75 ± 0,3 km have similar widths to the Namib ridges. The sand sizes of the Kalahari and Namib sands do, however, appear to be fairly similar (Table 3) with a range from 0,5 mm to 0,07 mm. The crests of the Namib dunes appear to have slightly coarser sizes than sand taken from the slopes, though more detailed sampling is required to show this for certain (Figure 10).

Table 3. Comparison of Namib and Kalahari sand.

B.S. Sieve No.	Mean % Grain sizes Namib	Mean % Grain sizes Kalahari	Cumulative % finer Namib	Cumulative % finer Kalahari
30	1,15	3,52	98,70	95,84
44	8,97	8,85	89,74	86,98
60	36,85	19,22	52,89	67,76
85	29,45	37,37	23,44	30,39
100	11,51	10,85	11,93	19,53
150	8,42	14,05	3,52	5,48
200	2,60	4,04	0,91	1,44
Pan	0,91	1,44	—	—

(Mean values determined from 15 samples of dune sand from Gobabeb, and 9 samples of dune sand in the southern Kalahari).

Other sand characteristics:	Namib	Kalahari
Hazen's Coefficient of Uniformity	0,67	0,67
Mean Size	2,11	2,21
Standard Deviation	1,71	1,76
Skewness	0,04	0,03
Kurtosis	1.30	1,35

Inland from the coast, behind the coastal dunes between Swakopmund and Walvis Bay there are sometimes a few small isolated dunes, but the only other major accumulations of sand are those on the east-facing sides of the larger inselbergs such as

Table 2. The nature of winds at Gobabeb.

Direction	Velocities (km/hour) 5-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54
NE	108	14	14	16	5	4	6	1
E	217	40	58	49	26	20	2	1
SE	886	73	26	19	3			
S	554	7	15	4				
SW	797	231	91					
W	829	48	5					
NW	936	54	9	1				
N	1423	109	32	8	4	2	2	
TOTAL	5750	576	250	97	38	26	10	2
Calms	1448							

Data (in hour frequency) for year December 1966 to November 1967 with exception of 6½ days with no records in February 1967.

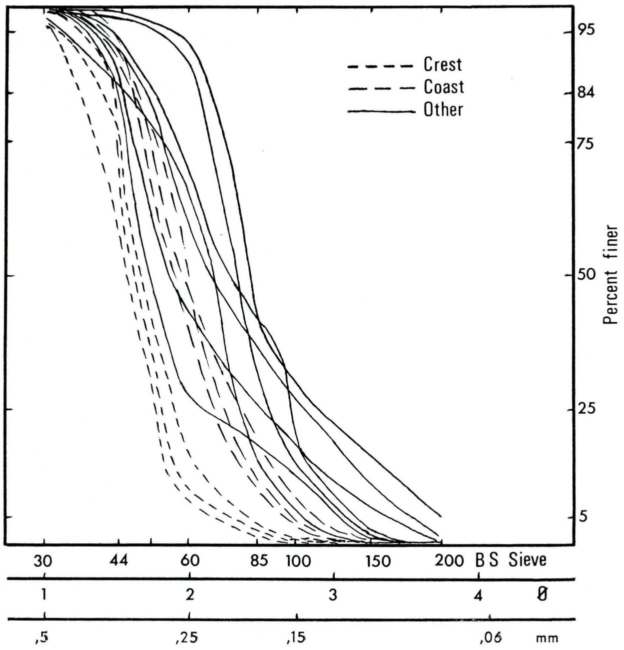

Figure 10. Grain size distribution of Namib Sands at Gobabeb and the Coast (near Swakopmund).

Khan Mountain and Rössing Mountain. The sand accumulation from the easterly berg winds at Rössing extends over 90 m up the mountain side, with a slope of 18°. The sand which forms the accumulation is coarser than the average for the Namib due to the contamination by weathered schistose rock from the steep rock slope above (Table 4). These 'sand glaciers' appear to be analogous in form to the debris-mantled sand cascades described for the Mojave Desert in California by Smith (1967).

Table 4. Rössing sand accumulation grain sizes (%).

Sieve No. (B.S.)	1	2
30	46,48	34,20
44	13,86	10,71
60	12,34	11,79
85	13,03	14,97
100	4,80	6,87
150	5,72	10,60
200	1,89	4,93
Pan.	1,89	5,94

THE INSELBERGS AND THE PLAINS

Spreitzer (1966) has reviewed the chronology of denudation in the Central Namib. He suggests that the inclined plane of the Namib, which rises to 900-1200 m, consists of several surfaces related to higher still-stands of sea-level than that of the present. He places the breaks between these surfaces at 200, 400, 600 and 900 m above present sea-level. Views across the Kuiseb Canyon show how clearly the highly folded beds have been planed off at some stage. Above all these levels another surface has been postulated, and it is represented by the dissected mass of the Khomas Hochland, which forms the eastern boundary of the desert. L. C. King has suggested that it might be a remnant of the Jurassic surface which he supposes to occur over much of southern Africa. Martin believes that there is also a pre-Triassic surface remnant (pers. comm. to Logan, 1960) that has been re-exposed from beneath younger beds, and in contrast, Kaiser (quoted by Gevers, 1936) suggests that the main summit level was formed in a Cretaceous humid period. The general consensus of opinion, as reviewed by Logan (1960), is that the surfaces are essentially fluvial.

Rising above the Namib plains are a large number of ridges and isolated mountains, the form of which, and also the abruptness of which, is related to lithology. The best developed pediments, generally with a slope of 4°, develop in granite, whilst granite and granite-gneiss inselbergs generally have the most rounded forms. The granite pediments are rock cut, and the inselbergs are oversteepened at the base. It seems reasonable to accept that the property possessed by granite in an arid environment of breaking down abruptly from boulder size to constituent grain size, combined with weathering at the base of slope, is the major factor in slope formation. Also, in spite of the low rainfall, aerial views of the area around Mirabib, Swartbank, and other inselbergs, shows the rôle of anastomising streams in removing fine-grained material from the pediments. Nowhere has much talus accumulated to obscure the well-marked break in slope between pediment and inselberg, though dolerite and some schist, because they break down in a more continuous fashion, sometimes show greater accumulation of debris. The rills, which must remove much of the fine material from the pediments, are marked by the presence of lines of bushes and grass in an otherwise largely vegetationless area. Wind seems to be relatively unimportant in the shaping of slopes in the Central Namib, though one does see some minor undercutitng of rocks. Gypsum crusts and desert pavement protect much of the area from deflation and there are not the atlernating bands of resistant and less resistant sedimentary rocks to give typical wind erosion forms so characteristic of the Southern Namib. In the Pomona area, for example, Kaiser (1926) described "Die Korrosions-Landschaft der Rücken und Kuppen" in the dolomite of the Nama System. Moreover, in the Central Namib, as Gevers (1936) pointed out, the wind is not nearly that powerful agent of erosion that it is in the Luderitzbucht littoral, about which Cloos (1954) wrote:

> "Here, for almost nine months of the year without a break, the wind devours the land. It gnaws away the rocks as hungry goats gnaw harsh grasses and thorny bushes . . . armed with . . . glass-hard quartz-shot, the wind ceaselessly pelts the mild slate and the waxy soft limestone, the hard granite and its schistose, somewhat less durable brother, the gneiss. Quickly, as if melted, the soft rocks disappear."

Nevertheless, there are some significant deflation forms in the Central and Northern Namib. Some are visible on the west side of the road from Walvis Bay to Rooibank, whilst Maack (1966) mentions deflation basins of considerable extent in the Stormberg Sandstone between the Koichab and Hoarusib Rivers.

The desert pavement characteristic of the gravel plains of the Namib may in part result from the deflation of fine materials to leave a coarser residue at the surface. Such desert pavements are well documented for other areas (Commonwealth Bureau of Soils, 1966), and exist in other parts of southern Africa, partcularly in the area to the south of Kenhardt, Cape Province. The relief on some of these pavements can be measured in cm per hectare, and their surfaces, judging by the way in which vehicle and other tracks remain even after strong winds, seem to have developed a certain stability. In other areas of the world it has been shown by field observation and laboratory experiment that alternate expansion and cracking of the soil during wetting and drying can result in upward movement of stones (Springer, 1968; Jessup, 1962), but this process can only be of limited utility in this extremely arid area.

QUATERNARY CLIMATIC CHANGE IN THE CENTRAL NAMIB

The whole history of climatic change in southern Africa is most uncertain, and the whole old chronology based on the Vaal River Terrace sequence has been shown convincingly to be inadequate (Partridge and Brink, 1967). One of the most fundamental problems in southern Africa is the absence of materials that can be reliably dated by isotopic means. Organic carbon materials and pollen are rare, and inorganic carbonates like calcrete are at present the subject of severe doubts (Ruhe, 1967). However, that there has been several marked fluctuations in the Kalahari Desert in the Pleistocene cannot be doubted (Grove, 1969), but the climatic relations of the Namib are such that a marked change in the Kalahari does not necessarily mean a similarly marked change in the Namib. Moreover, evidence from the river valleys of the Namib, which have their sources in the Highlands, would essentially be external evidence. However, tufaceous cave deposits in the Erongo Mountains (Martin and Mason, 1954) and a suggestion by Korn and Martin that there was a widespread Middle Stone Age pluvial in the Naukluft, are of more relevance to the Namib. In addition, as mentioned previously, Martin has shown that near the coast calcrete is being altered to a gypsum and that it is thus a fossil feature, probably the result of wetter conditions. Although climate is but one feature controlling soil genesis, it would seem from work carried out by French soil scientists in North Africa, and by myself in Libya, that calcrete it only forming at present in moderately moist semi-arid zones where rainfall is around 400 mm per annum. In southern Africa, many calcretes, which by their relationship to present valley incision, are young, and which appear to be fresh rather than weathered, sand-blasted or dissolved, are present on the wetter margins of the Kalahari in areas with around 250-300 mm annual rainfall. It is conceivable that the Namib calcretes formed under similar conditions, though no reliable figures can possibly be given.

There are two further lines of evidence which point to moister conditions during the Pleistocene in the Central Namib. The first comes from the study of the fauna and sediments of the raised beaches further to the south by Carrington and others at the South African Museum, Cape Town. Evidence of a warm water fauna has been found, indicating a change in the nature of the Benguela Current, which would probably greatly change climates in the coastal zone. The coarse nature of some raised beach material would also indicate the provision of larger quantities of cobbles in streams draining to the Atlantic. This is particularly true of the 17-21 m terrace on the Namaland coast (Carrington, per. comm., 1968; and Carrington and Kensley, 1969). Haughton (1931) also found evidence of warm water faunas on this west coast of southern Africa. The second line of evidence comes from soil studies near Gobabeb by Scholz (1968). He has described a fossil, red-brown soil from just east of the Kuiseb, which lies below the gypsum crust, and has all the characteristics of being formed under alternating warm and moist conditions. The soil has the following profile:

Depth (cm)	*Horizon*	
0-3	A	Ochre brown, gritty sand with incoherent fabric, covered by a loose layer of quartz grit.
3-7	Ca_1	As above, but containing $CaCO_3$.
7-30	Ca_2	Brownish-yellow, somewhat loamy sand, rich in $CaCO_3$, with polyhedral fabric and a loose network of roots.
30-40	Y	Yellowish-white, very coherent gypsum crust free of $CaCO_3$.
40-80	fCY_1	Reddish-brown clay, partly consolidated by gypsum.
80-100 +	fCY_2	Reddish-brown clay-gypsum crust with scattered white specks.

However, there seems to have been insufficient moisture for the Tubas, which rises within the Namib, to incise itself at all deeply into the Tubas Flats or to breach the coastal dune chain. Moreover, the superbly endemic fauna of the Namib has been seen as evidence of the permanence of arid conditions in the Desert. Koch (1960) wrote: "The limited exploration so far carried out shows that the endemic tribes, genera, and species far outnumber those found in other deserts of the world and in no other deserts do we find species showing such extreme specialisation and adaptation. This leads to the conclusion that the richness and endemism is due to the long and undisturbed duration of the peculiar climate and conditions obtaining in the Namib." In 1961 Koch reported that of wingless ground Tenebrionid beetles, 2 tribes, 35 genera, and 200 species are endemic to the true Namib from the Orange River to just north of Moçamedes, and again remarked that this suggested "the long and undisturbed duration of the special biota". Further ecological work since then on other aspects of the fauna near Gobabeb supports Koch's views on the superb endemism and adaptation of the Namib fauna. It is possible, however, that this apparent dichotomy between the geological and faunal evidence can be solved in terms of the shifting of the desert as an entity through a latitudinal range, so that areas were subjected to alternate wetter and drier conditions and the fauna moved as the desert moved.

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Figure 11. Micro solution rillen on marble at Swartbank.

Figure 12. Honeycomb weathering in granitic rock near Gobabeb.

Figure 13. Splitting of schist outcrop near Gobabeb.

Figure 14. Tafoni in granite at Gobabeb.

Figure 15. Lichens on weathered dolerite boulder at Swartbank.

Figure 16. Sand accummulation on the east side of Rössing Mountain.