THE GEOMORPHOLOGY OF THE CENTRAL NAMIB DESERT NEAR GOBABEB

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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 50 - 90 miles, though towards the north it narrows considerably - 47 miles near the mouth of the Cunene and only about 7 miles near Moçamedes. The desert rises to about 900 metres 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 90 miles and a latitudinal extent of around 250 miles. North of the dune area is the Damara or Northern Namib. Except in the coastal belt between the Kuiseb and Swakop Rivers it is largely free of sand. Within the southern Namib the great German geologist, Kaiser (1926), 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. Most of the field work was done at the Namib Desert Research Station at Gobabeb, which is about 70 miles south-west of Walvis Bay on the Kuiseb River (Diagram 1). Indeed the area in question is that covered by NASA Gemini V Colour satellite photograph S-65-45578. (NASA, 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 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.

THE GEOLOGY OF THE CENTRAL NAMIB

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

The area appears on the 1:1,000,000 Geological Map (Geological Survey of South West Africa, 1963).

Basically, the Namib Platform in the area is underlain by late Proterozoic 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 phenocrysts of orthoclase and microline felspar. The Damaran metamorphics are very variable, and include the mica schists, marble, granitic geniss, and quartzite.

Among younger intrusive rocks are black dolerite dykes. These usually show up clearly as linear ridges on air photos, 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. 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 in detail the climatic conditions of the Central Namib. This has already been done competently by Logan (1960). 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 23mm. Since 1899 the rainfall at Swakopmund has averaged 14mm. This compares with about 15mm for

Luderitz, in the southern Namib, and is similar to that for various other coastal deserts. (Meigs, 1966). Port Etienne (Mauretania) has 35 mm., Aden has 45mm., and El Refugion (Baja California) has 62mm. The rainfall in the Atacama is perhaps very slightly lower, with 1mm. being given as the mean annual rainfall for both Arica and Iquique.

The rainfall increases steadily towards the Great Escarpment, as the rainfall map shows.

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 16.5mm., but 22mm. have been recorded in a day at Goanikontes (on the Swakop River) and 740 mm. at Donkerhuk in one year (88mm. in one day). In 1934, 153mm. of rain fell at Swakopmund. The highest daily falls reported in the handbook, Weather on the Coast of Africa, (1944) are 15mm. for Walvis Bay, and 9mm. for Luderitz. In 1909 625mm. was recorded for Neuheusis, compared with only 80mm. in 1911. This variability is similar to that in parts of the South American West Coast desert. For example, Preston James (1959) writes: "At Trujillo, between 1918 and 1925, the total rainfall was only 1.4 inches; but during the month of March, 1925, a total of 15.5 inches fell, and on the three days from the 7th to the 9th rainfall was 8.9 inches."

The geomorphic significance of such rare events of high magnitude does not need stressing for an arid envioronment. Stengel (1964), for instance, has shown that the flood of 1934 at Swakopmund transported 35,000,000 m^3 of sand 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 70 miles inland. The fogs do not have the same duration as those at Port Nolloth (Republic of South Africa) - (See Weather on the Coast of Africa, 1944). At Gobabeb itself, in spite of its distance inland, fog was present at the station itself, or in the neighbourhood, on an average of 102 days for the years 1964 - 1967 inclusive. Whilst the fog only precipitated on an average of 60 days in the year, this produced a precipitation of 31mm. per annum, a figure slightly greater than the rainfall itself. Boss (quoted by Eriksson, 1958) estimated the yearly fog precipitation at Swakopmund to be 35 - 45 mm., compared with 20mm. at 40 km. inland. Daily quantities are small, though 6.5mm. has been recorded in one day at Gobabeb.

Thus, the fog brings a significant quantity of moisture into the desert, and this, coupled with its chemical characteristics, may have very considerable ecological and geomorphic significance. This point is expanded later in this report.

The winds are another very important part of the desert environment. The wind data in diagram 3 give an idea of the annual variability of the winds. At Gobabeb, east and south east winds are at a maximum frequency in winter and have mean velocities up to 21 km/hr, though actual velocities may exceed 50 km/hr. Winds from the north west show their heighest frequency in summer but have considerably lower velocities. In January diurnal variation is slight, but in the winter (July) the direction is south easterly at night until about 1000 hrs. 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 6 (Beaufort) and gales are common; but at Walvis Bay winds of force eight are rare. Inland, at Gobabeb, velocities seem to be even lower (Diagram 6). 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." Diagram shows the greater variability of direction, which, combined with lower velocities, makes the Central Namib around Walvis Bay a very different sort of geomorphic environment to that at Luderitz.

The work of Bagnold (1941) has shown that sand flow varies as the cube of the wind velocity over and above the constant threshold velocity at which sands begin to move. The threshold velocity is generally approximately 20 km/hr. (Bagnold, 1941, p.69). The diagram constructed to show frequency and velocity of wind for each of eight directions at Gobabeb for one year stresses very clearly the importance of the relatively infrequent east and north easterly winds (Diagram 4). This topic is returned to later in the discussion of wind erosion and dune alignment and formation.

The last aspect of the climatic background is that of temperature. The whole of the coastal Namib shows a remarkable similiarity in average monthly and yearly temperatures (Diagram 7). The temperature ranges are also small.

GOBABEB WINDS:

Vt

Velocity (km/hr)	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54
Direction										
NE	70	25	13	14	14	16	5	4	6	1
E	139	43	35	40	58	49	26	20	2	1
SE	520	222	144	73	26	19	3			
S	193	224	137	7	15	4				
SW	202	267	328	231	91					
W	268	353	208	48	5					
NW	361	354	221	54	9	1				
N	563	552	308	109	32	8	4	2	2	
Total	2316	2040	1394	576	350	97	38	26	10	2

Vt

Data from NDRS (Gobabeb) for year 1966 (December) to 1967 (November). Readings taken hourly throughout year, with exception of 6½ days in February 1967.

Total calms (winds less than 5 km/hr) = 1448

The mean annual range betwwen the warmest and the coldest months is 9°C. at both Walvis Bay and Swakopmund (Rumney, 1968), whilst 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 the coastal areas of the Namib, though temperatures of over 40°C. have been recorded on occasions, generally in association with strong easterly 'berg' winds. In general, however, the Namib does not suffer from any very great extremes of temperature. This fact may be of some significance in terms of rock weathering.

ROCK WEATHERING

The weathering of rocks under conditions of very low rainfall has been a major theme in arid geomorphology, with much of the work having been undertaken by German scientists. Some of the early work was summarised in Walther's classic review, and there is no doubt that material from the Namib played a part in the formulation of his views. Certainly the Namib shows many 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 illustrate 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 30mm. in diameter, and up to 15mm. deep. They show no marked orientation 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 cemetation of rock so that it presents more resistant and upstanding outer surfaces, is particularly well-developed along joints in the granite. A photo from the Research Station grounds is shown. It seems to be restricted to granite. 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 200mm. thick may spall off, they are frequently much thinner, and one photo shows the author holding a 20mm. slab from a granite outcrop within the dunes. 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 80cm. across as against entrances with diameters of 20cm. Such features also occur in granite south of the Brandberg Mountain. There are a large number of reports of tafoni in the literature from other parts of the world. The type-site is Corsica, whence the name, an alternative for alveolation, is derived. (Reusch, 1882; Tuckett and Bonney, 1904). They are particularly common in granitic rocks, and are well-developed in Antarctica (Prebble, 1967), and Wilhelmy (1964) cites Elba, Aruba, Peru, N.W.India, and the deserts of central Asia.

Finally, much of the granitic debris has broken down into its constituent grain sizes - granular disintegration.

These various forms, though best developed in the granites of Gobabeb, Rooikop, and Mirabib, do also occur in schistose rocks. Dolerite, on the other hand, tended to show different weathering characteristics from the other rock types. Generally it had a black, or dark red brown patina, and it tended to break down into large boulders and cobbles. In this it was different from many other rocks which showed a rather more abrupt break-down into constituent grain sizes. 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 the photo shows a reasonably common anvil-shaped weathering remnant.

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. In addition to the rillen there are small pock marks and brown staining. That the marble has undergone some solution is also evidenced by the relatively high calcium carbonate content of the gypsum crust developed on and around the Swartbank inselberg. This is discussed further in the section on Crust Formation. In places the surface of the gypsum crust itself shows minor weathering to give vermiculations - pitted and ridged micro-relief.

WEATHERING FACTORS

Insolation was given its original meaning of splitting due to the effect of expansion and cooling through solar heating by Walther (1900), and his ideas rapidly became widely applied in Egypt, Sinai, and elsewhere. Grotefeld, an early worker in the Namib (quoted by Calvert, 1916), talked 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) continues to believe in mechanical disruption of rocks, and Ollier (1963) and Greenwood (1962) 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: "Gradients in a granite structure resulting from the usual diurnal temperature changes cause internal stresses which, after numerous repititions 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 (1964) 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 'Zersplatung' (splitting), a term which allows splitting effects besides solar heating. The change in attitude has resulted from the theoretical and experimental work of Grigg and Blackwelder, and from the field work of Roth. (1965). In the context of the Namib it must be said that temperature fluctuations are not particularly severe compared with those in certain other desert areas, including the Kalahari, though sand surface temperatures at Gobabeb in 1965 showed a maximum annual range of 70.5 degrees, and the maximum diurnal range was about 50°C. The temperature variation, both annual and diurnal, falls off very rapidly beneath a thin cover of superficial material, as the graph 8 shows. I made measurements of diurnal temperature fluctuations beneath different thicknesses of granite slabs resting on sand at Gobabeb, and found the changes illustrated. These changes are less than those found by Routh in the Mohave Desert, and he showed that insolation was not a cause of quartz monzonite breakdown there. (Diagram 9)

Moreover, 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 (1950) experimental work showed that granite suffered from expansion effects caused simply by wetting.

An alternative factor involved in rock weathering in the Namib Desert may be salt crystallisation. Wellman and Wilson (1965) describe salt crystallisation as, "A powerful undercutting agent that constantly tends to steepen slope 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 in the fog. Eriksson (1958) working on Boss's data for Swakopmund, suggested a yearly precipitation of atmospherically-derived salts of 120 kg./ha.*. 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. My own observations of fog water from drips and precipitation in the self-recording fog gauge at Gobabeb during May and June 1968, showed electrical conductivity readings of great variability, though most readings suggested a TDS content of between 100 and 1000 ppm. All samples were alkaline.

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* This compares with 130 Kg/ha for the Israel coastal tract. (Eriksson and Khunakasem, 1969).

The appreciable frequency of application of a thin spray of salt-rich water by the mist, followed by 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, as shown in a later section, is very rich in gypsum and saline crusts, and dust from these would contribute salt by direct deposition on surfaces and in cracks.

The crusts may themselves be of some importance in breaking up underlaying rocks. Soil pits dug by the author where gypsum overlies granite shows how the gypsum penetrates the granite and breaks it up. Road workings on basalt outcrops inland from Swakopmund show that gypsum veins have penetrated and split the basalt to a depth of over 20ft. Around Mirabib surface limestone (calcrete) is breaking up underlying schists, whilst on the top of Swartbank a gypsum/calcium crust is breaking up the marble. A photograph from a small gully near Gobabeb shows the exhumation of some highly weathered granite from gypsiferous terrace material.

Chemical weathering is evidenced in the Central Namib in the form of rillen and staining on marble, stainings and patinas on other types of rock, case hardening on granite, and the oversteepening at the bases of some granite inselbergs. Furthermore, Scholz mentions an iron hat on a dyke of ultrabasic dunite in the Kuiseb area. However, Logan (1960) has reported that "the cleavage faces on feldspar and mica are still untouched by weathering indicating that mechanical weathering is of sole importance." My own observations show that this is not so, and Scholz reports the presence of clay mineral formation in soils inland from Walvis Bay. 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 entirely absent. On the dolerites the lichens probably play an important role, for as Lowdermilk has suggested in America, lichens play a role in the mobilisation and deposition of Manganese and Iron to give varnished rocks. At Swartbank lichens of such species as Caloplaca elegantissima and Parmelia hottentotta (Geiss, 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. E.T.Oborn (1960) mentions that the iron content of lichens is on average 5.16 mgms per gm. of dry matter, compared with an average of only 0.30 mgms. per gm. dry matter for most land plants. Lichens are also present in large quantities on some marbles at Swartbank. The probable importance of lichens in desert weathering and crust formation has recently been discussed by Krumbein (1969).

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 crust. Scholz has already mentioned a few small polygons in some river alluvium along the Soutrivier, north west of Gobabeb, and his thesis contains plates (Abb. 47) illustrating some others. 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 United States, where they have resulted from desiccation and contraction. (Neal, 1965; Christiansen, 1963; Willden and Mabey, 1961; Long, 1943; and Neal and Motts, 1967.) Some of these polygons may be as much as 300 metres in diameter. Desert clay soil polygons and patterned ground are also well known. Alimen (1953) reports them from North Africa, and Ollier reports them from South Australia (1966).

However, the gest 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.

Like most natural polygonal features, such as some tundra soils, columner structures in basalt, and mud cracks (see D'Arcy Thompson (1961)) the polygons are random orthogonal polygons (Lachenbruch, 1962) with a tendency towards hexagonal and pentagonal shapes. Because of imperfect development of some fissures the ideal hexagonal shape is not always reached at Gobabeb, and even in cohesive and homogeneous clay this is frequently the case. Examination of several mud-crack photographs from various sources resulted in an average of about 5.10 sides being found for a sample of 200 polygons. With the rather variable material in the Gobabeb crust it is not surprising that perfect hexagons do not develop. However, stripes or elongated polygons do not appear to be common. Some of the polygons have internal dimensions of upto 20 m. across, though between 8 and 9 m. is the average size. The polygons show various forms: the largest polygons have a raised margin of whiter calcareous gypcrete (calcium carbonate content about 25-40 %) which may have a relief of 40 cm. (See photo). Other polygons are marked not by ridges but by depressions along fissures and may or may not have upturned edges (see diagram 10). Other polygons may have very slightly raised middles, with pebbles forming rings around the dome, though this form is rare in its perfect form.

The polygons occur on the flat surface of the gypsum-calcrete terrace which lies at about 45m. above the south bank of the Kuiseb. The terrace extends well into the dune area. The crust is many feet deep, with almost the whole terrace being cemented to a greater or lesser degree. The bulk of the cemented material is of sand size (see grain size diagram) and is capped by, and contains some, well-rounded, wind polished, fluvial pebbles, (diagrams 15, 16).

Because of the minimal rainfall of the area it is difficult to attribute the polygons to wetting 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.

Both topographic position, and relative lack of clay minerals, seem to exclude any idea that they are formed by playa desiccation or by expansion and contraction of clays. These have been the two favourite explanations for patterned ground in other arid lands. Any explanation through frost action, akin to that occurring in tundra envioronments, is ruled out by the present almost complete absence of frost. Evidence from elsewhere in South West Africa does not suggest a particularly cold period in the period since the formation of the terrace upon which the polygons rest (probably Upper Pleistocene). The raised nature and different characteristics 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 has yet to be fully explored. Thus, unless there was some increase in humidity since the terrace was formed, it is difficult to give any satisfactory explanation for the polygons. It is particularly difficult to explain the great size of the polygons, though the thickness of the crust may be one possible reason. Thin crusts can generally sustain only small polygons, though this varies very greatly with the physical properties of the materials involved.

Another sort of patterned ground is caused by the trapping of sand by scattered masses of vegetation to give pimpled ground. This is particularly evident on air photos of the valley fringes and the coastal zone around Swakopmund. <u>Acanthosicyos horrida Welw.</u> and <u>Citrullus ecirrhosus Cogn</u> (both Cucurbitaceae) are responsible for such mounds, but <u>Salvadora persica</u> gives some of the clearest examples. (See photo). The mounds, which show similarity to the phreatophyte mounds around playas in the United States, average about 50m. in diameter, and are generally about 3 - 4 m. in height. Some of the pimpled ground of the Western Cape, in the Malmesbury area, locally called heuveltjies, may be largely relict mounds formed under more arid conditions.

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 4m. 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 calcium carbonate. Martin (1963) describes the location of some of the higher grade deposits, and believes that the gypsum crusts result 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 (for example, north east Africa) the present author is not sure. In the vicinity of marble ridges and inselbergs the gypsum contains above average quantities of $CaCO_3$, and 3 samples from Swartbank had $CaCO_3$ contents of 44.5%, 21.6% and 35.14%, thus showing the local effects of the highly calcareous marble (96% $CaCO_3$). 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%.

No particularly marked change is evident in the composition and character of the crusts until one is about 60 - 70 miles 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 particularly well developed in the small, shallow drainage lines running from inselbergs, probably because of the local presence there at certain times of more soil moisture. This particular calcrete may for that reason have no particular age or palaeoclimatic significance. It is seldom more than a meter 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 rims to give a feature of marked geomorphic importance. The spread of the calcification process has led to the slight disruption and doming of the underlying rocks, and has also tended to form in circular masses. Such 'boils' are seldom more than 3 - 4 m. across and do not, therefore, compare in size with 'calcrete anticlines' described by Jennings and Sweeting (1962) for Western Australia, and also known in the clacrete surrounding the Etosha Pan.

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 has described Upper Pleistocene terraces at 40 ft. above present drainage level. Such low, calcareous terraces also line the Tubas.

THE KUISEB RIVER

The Kuiseb rises in the Khomas Hochland near Windhoek, and, as a result of the relatively high rainfall and runoff in that area, is the first major river to reach the Atlantic north of the Orange River. 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 wadis, like the Sout Rivier bring in some flow from the north 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 the other rivers of the north and central Namib, the long profile of the river shows a tendency towards convexity, rather than the concavity characteristic of most rivers. (See diagram 12 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, 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.

The river 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. Speitzer (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 diagram 11. 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 maintaining 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 (Vegter, 1953) 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. It seems possible that they were formed in the not too distant past by the ponding up of the Kuiseb. If they were of any great age one would suspect they would have become cemented like the Upper Pleistocene terraces along the river not very far to the west. However, the river bed is now incised deeply into bedrock, and the gorge into which the sediments were deposited must be of considerable age. In many places too, especially to the east of Gobabeb, the incision of the stream bed suggests that a shift to the north has not taken place in the very recent past.

The reason why the dunes stop so abruptly at the Kuiseb is that such big dunes 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 lesser influence of river floods at the mouth, and 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. In addition rare northerly winds of high velocity would play a role in keeping the dunes from crossing the River. A further possibility is that the dunes have only recently reached the River, and that the northern boundary of the dunes co-incides with the Kuiseb purely fortuitously. There is some support for this idea from the eastern part of the dunefield, for a German geological map of 1912 shows a road or track running on the south side of the Kuiseb as far west as Natap. (Range, 1912).

Towards the Kuiseb Gorge north bank, tributaries of the Kuiseb, like those of the Swakop, have cut back into the Damara rocks, largely schists, to give a badlands type of scenery. This has been termed the 'Gramadullas'.

Whilst some of the gullies may be the result of past wetter periods, it seems likely that infrequent storms of high intensity could, in the course of time, erode the landscape in this way. The Swakop is lined by a much more incised series of gullies in its lower course than is the Kuiseb, and, as the satellite photo clearly shows, is more constricted by banks.

THE DUNES OF THE NAMIB

The dunes of the Namib are reputed to be the biggest in the World, and examination of staellite photos taken by the astronauts of Gemini 4 and Gemini V suggests a broad similarity with those of the Empty Quarter of Arabia (NASA, 1967, pp. 23, 47, 137) and with those of southern Algeria (p. 154). They are basically linear dunes averaging near Gobabeb about 80 - 100 m in height. Near the Sossus Vlei, however, they have been reported as reaching 250 or 275 m in height above the surrounding plain (Jaeger, 1939, p. 19). The Sossus is one of the three major vleis - the other two being the Tsondab and Kuichab Vleis - which fails to breach the massive dunes. However, the staellite photo of the Namib does suggest some discontinuity in the dunes to the west of the Tsondab vlei.

The main trend of the dunes is approximately from north to south, and it is probable that easterly winds are responsible for this trend as they are dominant at velocities greater than the threshold velocity required for the movement of sand. Near the coast, as the satellite photo shows, some dunes trend approximately NE to SW, and this probably results from the relatively higher velocities nearer the coast which enable the very frequent south westerly winds to play a greater role in sand movement than they do further inland where velocities appear to be less. (Diagram 6)

Random measurements of 50 maximum dune slope angles shows the average lee (steep) slope to be just under 32°, and the average windward slope to be 25°.

These dunes are markely bigger 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. In the western Kalahari, near Koes in South West Africa, the dunes average only

80 feet (25 m.) and have inter-dune streets only 300 m. across, campared with 1000 - 1500 metres in the Namib. However, the spacing of some dunes near the Tsodilo hills in Botswana, together with their width, suggests that they may at one time have had a similar size to those at Gobabeb. The characteristics of Kalahari and Namib sand are generally similar. (See diagram 14).

The cumulative percent grain size diagram and tables shows the nature of the sand which forms the dunes in the Central Namib. The grain sizes lie between 0.5 mm. and 0.07 mm., so that the sand can be classed as medium, fine and very fine under the Wentworth Classification. Though the sample is not big enough to allow any firm assertions, the crests of the linear ridges seem to have slightly coarser sizes than sand taken from the slopes of the dunes.

Inland from the coast, behind the coastal dunes between Swakopmund and Walvis Bay (Samples, N/A18, N/A19, N/A17), 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 Khan Mountain and Rössing Mountain. The sand accumulation from the easterly berg winds at Rössing extends over 300 ft. (90m.) 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 of weathered schistose rock from the steep rock slope above. (Diagram 18)

THE INSELBERGS AND THE PLAINS

Spreitzer (1966) has reviewed the chronology of denudation in the Central Namib. (Diagram 19) He suggests that the inclined plane of the Namib, which rises to 900 - 1200m., 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 (see photo). 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 it is a pre-Permo-Triassic surface (personal communication to Logan, 1960) that has been re-exposed from beneath younger beds, and in contrast, Kaiser (quoted by Gevers, 1936) suggested it was formed in a Cretaceous humid period. The general consensus of opinion, as reviewed by Logan, 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 inselbergs which usually ~~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 envioronment 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 role 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 accumulations 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 vegetation-less area.

Wind seems to be relatively unimportant in the shaping of slopes in the Central Namib, though one does see some minor undercutting of rocks. Gypsum crusts protect much of the area from deflation and there are not the alternating 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 Korrasions-Landschaft der Rücken und Kuppen' in the Dolomite of the Nama system. Moreover, in the Central Namib, as Gevers remarked, 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 sandstein 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 coarse 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, particularly in the area to the south of Kenhard (C.P.). Much of the material forming these pavements is highly polished, whilst on the under sides quartzitic pebbles may be stained by green window algae.

QUATERNARY CLIMATIC CHANGE IN THE CENTRAL NAMIB

The whole history of climatic change in Southern Africa is most uncertain, and the old chronology of Van Riet Lowe et al based on the Vaal River Terrace Sequence, which for so long acted as a base, has been convincingly shown to be inadequate (Partridge and Brink, 1967). However, that there was a marked degree of climatic change in the Kalahari is not in doubt, 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 rivers of the Namib, which have their sources in the highlands of South West Africa, would essentially be external evidence. However, Korn and Martin have suggested a widespread Middle Stone Age pluvial for South West Africa, and in the Naukluft area (as reported by Söhnge and Van Riet Lowe) have suggested a pluvial period coinciding with the beginning of the Pleistocene, Martin and Mason, (1954) from a tufa deposit in Phillips Cave, Erongo Mountains, on the edge of the Namib, have suggested a slightly higher rainfall at one time during the formation of Bed II. Surface limestone, which probably needs a higher rainfall than that at present in the Namib, is widespread, but much of it may be Tertairy (Pliocene) in age, and the dating of the rest is uncertain. Smith suggest that a 40ft. calcreted terrace in the Swakop Valley is Upper Pleistocene in age. The fact that the Tubas River, unlike those rivers with their sources in the highlands, has been unable to penetrate the dunes or to dissect its course into the Namib Plain, suggests that there was insufficient rainfall within the confines of the Namib itself.

There are two further lines of evidence which point to moister conditions during the Pleistocene in the central Namib.

At the Cape Town Museum, Carrington is working on the fauna of the raised beaches along the coast of South Africa and South West Africa. He has found evidence of a warm water fauna in some of the raised beach material. The fauna indicates warmer temperatures in the Benguella Current, and this would almost certainly lead to higher rainfall totals. This confirms the earlier work of Haughton (1932).

Secondly, Scholz (1968) has described a buried fossil, red-brown soil from just east of the Kuiseb near Gobabeb. This fossil soil appears below the gypsum crust and is characteristic of alternating moist and warm climates. The soil has the following profile (Scholz, p. 102):

0 - 3 cm. A: Ochre brown, gritty sand with incoherent fabric, covered by a loose layer of quartz grit.

3 - 7 cm. Ca_1 : As above, but containing $CaCO_3$

7 - 30 cm. Ca_2 : Brownish-yellow, somewhat loamy sand, rich in $CaCO_3$, with polyhedral fabric and a loose network of roots.

30 - 40 cm. Y : Yellowish-white, very coherent gypsum crust free of $CaCO_3$

40 - 80 cm. fCY_1 : Reddish-brown clay, partly consolidated by gypsum.

80 - 120+ cm. fCY_2 : Reddish-brown clay-gypsum crust with scattered white specks.

The geological and geomorphic evidence for the Namib is therefore not very conclusive. The archaeological evidence is in a similar state. The ecological evidence, on the other hand, does not suggest any great degree of climatic change, for the Central Namib dunes have a uniquely endemic fauna, which is extraordinarily specialised.

Koch (1960) wrote: "The limited exploration so far carried out shows that the endemic tribes, genera, and species far out number those found in other deserts of the world and in no other desert 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 adaptation and endemism of the Namib fauna.

If the Namib has indeed undergone only minor climatic change it makes it of great importance for the study of 'true' desert geomorphology. Most other deserts, including the Atacama, seem to have undergone marked climatic change in the Pleistocene.

REFERENCES

Alimen H. (1953), Polygones de cailloux sur les sols désetiques, Colloques Internationaux du Centre National de la recherche scientifique XXXV, Actions aeoliennes, Phenomenes d'evaporation et D'Hydrologie superficielle dans les regions arides, Alger, 1951.

Bagnold R.A. (1941), The Physics of Blown Sand and Desert Dunes, London.

Birot P. (1954), Désagrétion des Roches cristallines sous l'action des sels, C.R.Acad. des Sciences de Paris, 238 (10) 1145-6.

Birot P. (1968), The Cycle of Erosion in different climates, trans. by C.I.Jackson and K.M.Clayton, London. 144 pp.

Blackwelder E. (1933), The Insolation Hypothesis of rock weathering, American Journal of Science, 26, 97-113.

Butzer K.W. and Hansen C.L. (1968), Desert and River in Nubia, Wisconsin 562 pp.

Calvert A.F. (1916), The German African Empire, Laurie, London,

Cloos H. (1954), Conversation with the Earth, trans. by E.B.Garside, London.

Clifford (1967), The Damaran Episode in the Upper Proterozoic-Lower Palaeozoic Structural History of Southern Africa, Geological Society of America Special Paper No. 92, New York.

Christiansen F.W. (1963), Polygonal Fracture and Fold Systems in the Salt Crust, Great Salt Lake Desert, Utah, Science, 139, 607-9.

Commonwealth Bureau of Soils (1966), Bibliography on Desert Pavement, Bibliography 980, (Mimeo), Harpenden, U.K.

Eriksson E. (1958), The Chemical Climate and Saline Soils in the Arid Zone, UNESCO Arid Zone Research, X Climatology, Reviews of Research, 147-180.

Eriksson E. and Khunakasem V. (1969), Chloride concentration in ground water, recharge rate, and rate of deposition of chloride in the coastal plain of Israel, Journal of Hydrology, 7 (2), 178-97.

Geiss W., (1962), Some notes on the Vegetation of the Namib Desert, Scientific Papers of the Namib Desert Research Station, VIII (3) 35pp.

Gevers T.W. (1936), The morphology of Western Damaraland and the adjoining Namib Desert of South West Africa, South African Geographical Journal, 19, 61-79.

Greenwood J.E.G.W. (1963) Rock Weathering in Relation to the Interpretation of Igneous and Metamorphic Rocks in Arid Regions.

Griggs D.T. (1936), The factor of fatigue in rock exfoliation, Journal of Geology, 44, 781-96.

Haughton S.H. (1932), Transactions Geological Society of South Africa, 34, p.19.

Hockmann A. and Kessler D.W. (1950), Thermal and Moisture Expansion Studies of Some domestic granites, U.S. Bureau of Standards Journal of Research 44, 395-410.

Jaegar F. (1939) Die Trockenseen der erde, Petermanns Mitteilungen, Erganzungsheft 236, 159 pp.

James P.E. (1959), Latin America. Cassell, London

Jennings J.E. and Seeting M.M., (1962), Caliche Pseudo-anticlines in the Fitzroy Basin, W.Australia, American Journal of Science 259, 634-639.

Kaiser E. (1923), Kaolinisierung und verkieselung als verwitterungs-vorgänge in der Namibwüste Südwestafrikas, Zeit. fur Krystallographie 58 125-46.

Kaiser E., (1926), Die Diamantwüste Sudwestafrikas, 2 Bde., Berlin.

Koch C. (1960), The tenebrionid Beetles of South West Africa, Bull. South African Museums Assn. 7 (4) 73-85.

Koch C. (1961), Some aspects of abundant life in the vegetationless sand of the Namib Desert dunes, Journal of the South West Af. Sci. Soc. XV, 1961, 9-92.

Krumbein W.E. (1969), Uber den einfluss der mikroflora auf die exogene dynamik (Verwitterung und Krustenbildung), Geol. Rundschau 58 (2), 333-62.

Lachenbruch A.H. (1962), Mechanics of Thermal Contraction Cracks and Ice-Wedge Polygons in Permafrost, Geological Society of America Special Papaer, 70, 69 pp., New York.

Lang W.B. (1943), Science 98 (1943), 583-584. Gigantic Drying Cracks in Animas Valley, New Mexico.

Leopold L.B., Wolman M.G., and Miller J.P., (1964), Fluvial Processes in Geomorphology, Freeman, San Francisco.

Logan R.F. (1960), The Central Namib Desert, South West Africa, Nat. Ac. Sci. Nat. Res. Council, Washington D.C.

Martin H. (1963), Gypsum Deposits of South West Africa, Trans. Geol. Soc. S.Africa, LXVI.

Martin H. and Mason R. (1954), Test Trench in the Phillips Cave, Ameib, Erongo Mts., S.W.A., S.African Archaeol. Bull. 36 (9), 148-51.

Martin H. (1965), The Precambrian in South West Africa, Cape Town.

Martin H. (1965), A Bibliography of Geological and Allied Subjects, South West Africa; Bulletin Precambrian Research Unit (Chamber of Mines) Cape Town Dept. of Geol., 1.

Martin H. (with H. Korn), 1955, The Pleistocene in S.W.A., Proc. of 3rd. Pan African Conference on Prehistory, p. 14.

Meckelin W., (1959) Forschungen in der Zentralen Sahara, George Westermann Verlag.

Meiggs P. (1966), Coastal Deserts of the World, UNESCO Arid Lands,

Merensky H. (1909), The Diamond Depositis of Lüderitzland, Trans. Geol. Soc. S.Africa XII, p.13.

National Aeronautics and Space Administration (1967) Satellite photos from Gemini 3, 4 and 5.

Neal J.T., Giant Desiccation Polygons of Great Lake Playas, Air Force Cambridge Research Lab. Office of Aerospace research, USAF environmental research papers, 123, (1965), 20 pp.

Oborn E.T. (1960), The Iron Content of Selected Water and Land Plants U.S.Geol. Surv. Water Supply Paper, 1459 - G.

Ollier C.D. (1963), American Journal of Science 261, 376-81.

Ollier C.D. (1966), Desert Gilgai, Nature 212 (5062), 581-3.

Partridge T.C. and Brink A., (1967) Gravels and Terraces of the Lower Vaal River Basin, South African Geographical Journal, XLIV, 21 - 38.

Prebble M., (1967), Cavernous Weathering in the Taylor Dry Valley Victoria Land, Antartica, Nature 216 (5121), p. 1194.

Range P. (1912), Geologie der Deutschen Namalandes, Beitr. fur Geol. Erforschung der Deutsch Schutz gebiet.2.

Reusch H.H. (1882), Geologie de la Corse, Bull. Soc. de Geol. de France, XI, 62-67.

Roth E.S. (1965), Temperature and Water as Factors in Desert Weathering. J. Geology, 73, p.454

Rumney G.R. (1968), Climatology and the World's climates, Macmillan, New York and London.

Schattner I. (1961), Weathering Phenomena in the Crystalline of the Sinai in the light of current notions, Bull. Res. Council of Israel, 10 G.

Scholz H. (1963), Studien üben die Bodenbildung zwischen Rehboth und Walvis Bay, Dissertation Dr. Agr. Bonn.

Scholz H. (1968), Die Boden der Wuste Namib/Südwestafrika, Zeits. fur Pflanzernahrung und Bodekunde, 119 (2), 91 - 107.

Smith D.A.M., (1962), The Geology of the Area around the Khan and Swakop River in S.W.A., Memoir 3, S.W.A. Series, Geological Survey S.Africa

Sparks B.W. (1960), Geomorphology, Longmans, London.

Stengel H.W. (1964) and (1960), The Rivers of the Namib and their Discharge into the Atlantic, Scientific Papers of the Namib Desert Research Station, No. 22, and No. 30.

Spreitzer H. (1966), Beobachtungen zur Geomorphologie der Zentralen Namib und ihrer Randgebiete, Journal S.W.A. Scientific Society, XX.

Thompson W. D'Arcy, (1961), On Growth and Form (abridged edn.), Cambridge.

Tuckett F. and T.G.Bonney (1904), Eroded Rocks in Corsica, Geological Magazine, Decade V, Vol 1. No. 482.

Van Riet Lowe C. and Sohnge P.H., The Geology and Archaeology of the Vaal River Basin, Memoir 35, Union of South Africa Dept. of Mines, Geological Survey.

Vegter J.R. (1953) Underground Water Supplies in the Crystalline Complex of the Kenhardt District C.P. and the Water supply of Walvis Bay, MSc Thesis, Faculty of Science, University of Pretoria.

Walther J. (1900 and 1924), Das Gesetz der Wüstenbildung in Gegenwart und Vorzeit, Leipzig.

Weather on the Coast of Southern Africa, (1944) Royal Navy and Royal South African Airforce Meteorological handbook.

Wellington J.H. (1955) Southern Africa, A Geographical Study, 2 Vols., Cambridge.

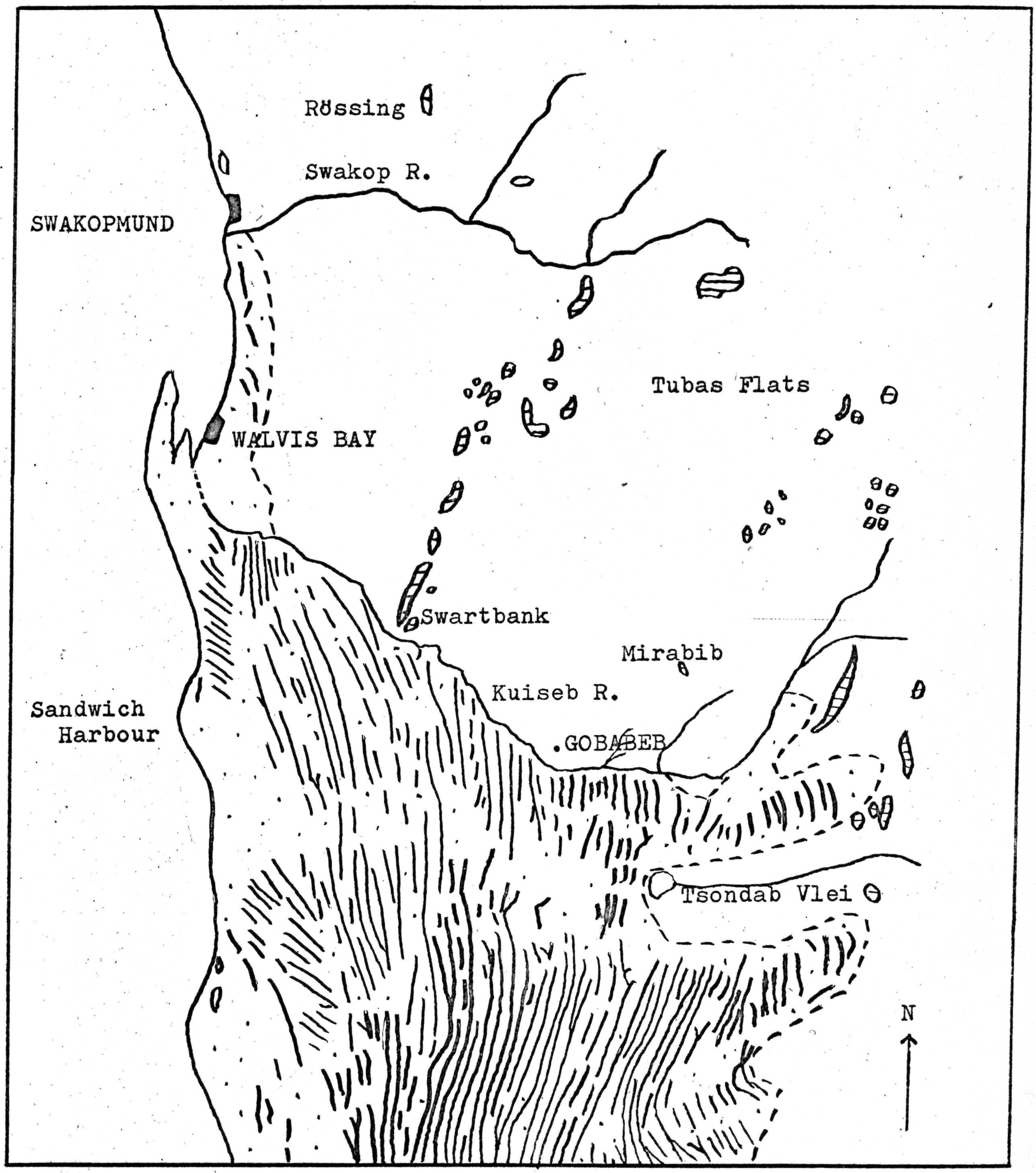
Wellington J.H. (1967), South West Africa and the Human Issues, Oxford.

Wellman H. and Wilson T. (1965), Salt Weathering, a neglected geological erosive agent in coastal and arid environments, Nature, 205, 1097-8

Wilhelmy H. (1964), Cavernous rock surfaces (Tafoni) in semi arid and arid climates. Pakistan Geographical Review 19 (2), 9 - 13

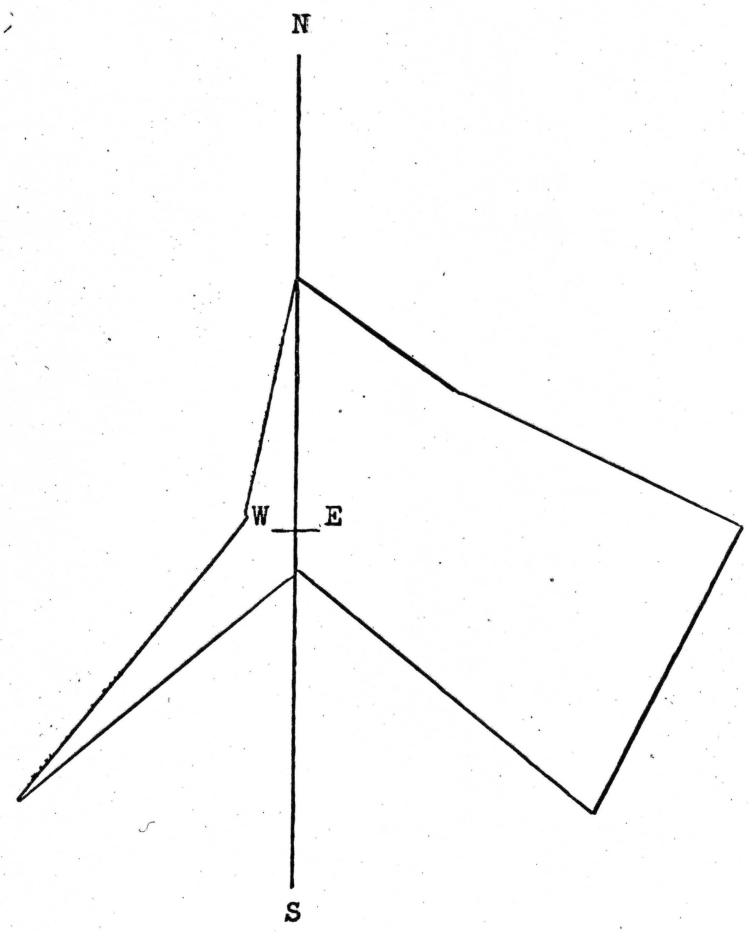
Willden and Mabey D.R. (1961), Giant desiccation fissures on the Black Rock and Smoke Creek Deserts, Nevada, Science 133, 1359-60.

Diagram 1



THE CENTRAL NAMIB

Diagram 4



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 TIMES THEIR FREQUENCY IN HOURS PER YEAR. (1" = 2,000,000).

(Constructed from the data in diagram).

Diagram 5

SURFACE WIND SPEEDS FOR WALVIS BAY AND LUDERITZ?

(At 1500 hrs.. Source, Handbook, 1944)

WALVIS BAY

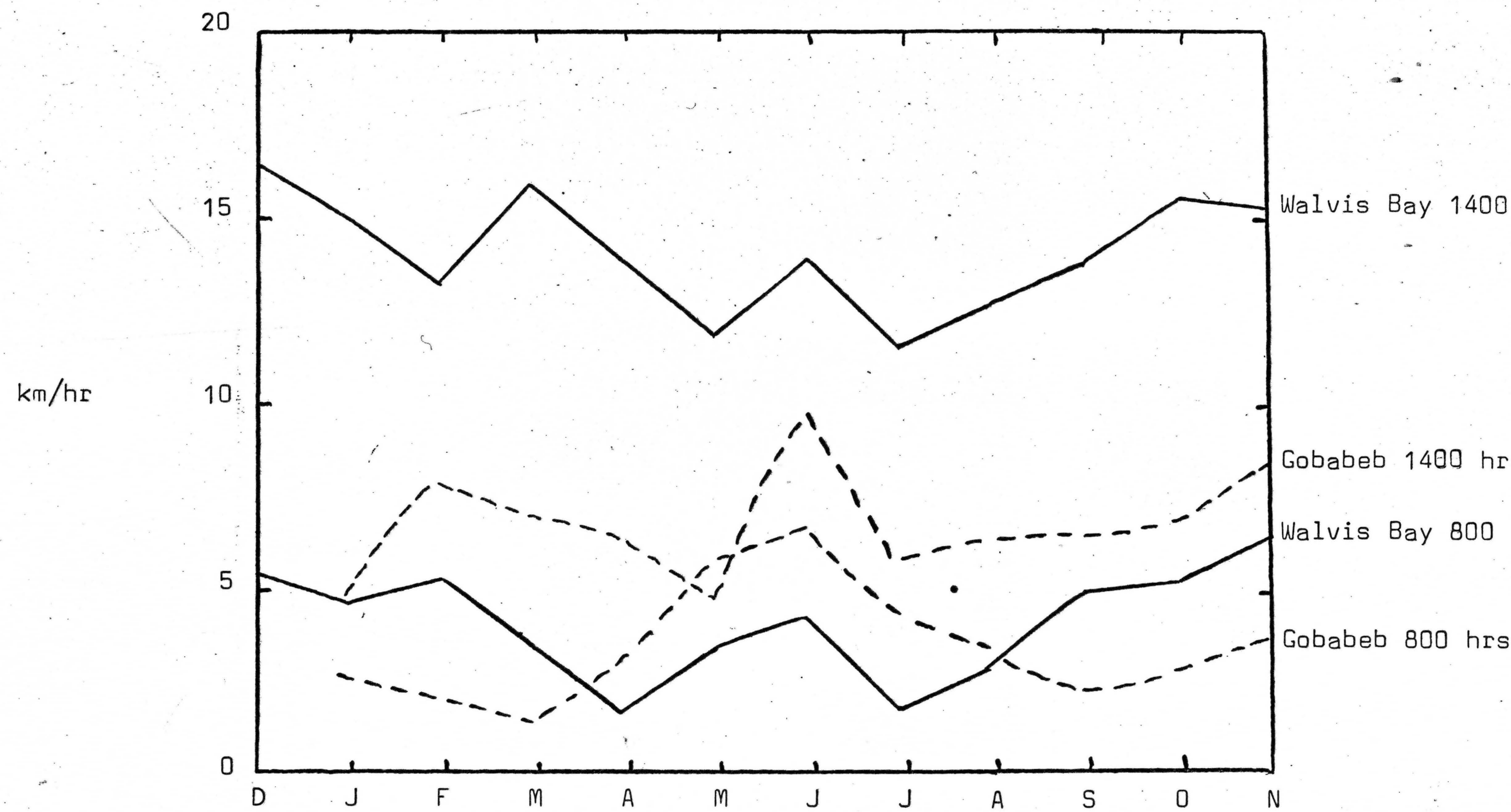
Month	km/hr	N	NE	E	SE	S	SW	W	NW	Less than 3 knots.
Dec-Feb.	3-13	1				1	34	21	8	4
	14-27					5	22	1	1	
	28-40					1	1			
Mar-May.	"					4	36	13	5	7
						9	24	1		
							1			
June-Aug.	"	3	1	1		7	33	8	9	8
						11	17			
						1	1			
Sept-Nov.	"	1				3	27	9	6	9
						12	28			
						3	2			

LUDERITZBUCHT

Month	km/hr	N	NE	E	SE	S	SW	W	NW	Less than 3 knots.
Dec-Feb.	3-13	2	1			3	5	3	11	5
	14-27					23	16			
	28-40					19	8			
	40+					2	2			
Mar-May.	"	3				11	10	3	8	10
						29	10			
						10	3			
						1	1			
June-Aug.	"	6			1	10	9	6	13	17
		1			1	17	7	1	2	
				1		6	1		1	
Sept-Nov.	"	1				2	7	6	16	5
						20	17			
						15	4			
						5	2			

Campare the frequency of events (%) ef wind speed 28-40 knots.

Diagram 6



MEAN WIND VELOCITY FOR 1400 HRS AND 800 HRS

FOR GOBABEB AND WALVIS BAY

Dec. 1965 - Nov. 1966

Diagram #7

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

	Arica.[2]	Port Etienne[2]
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:

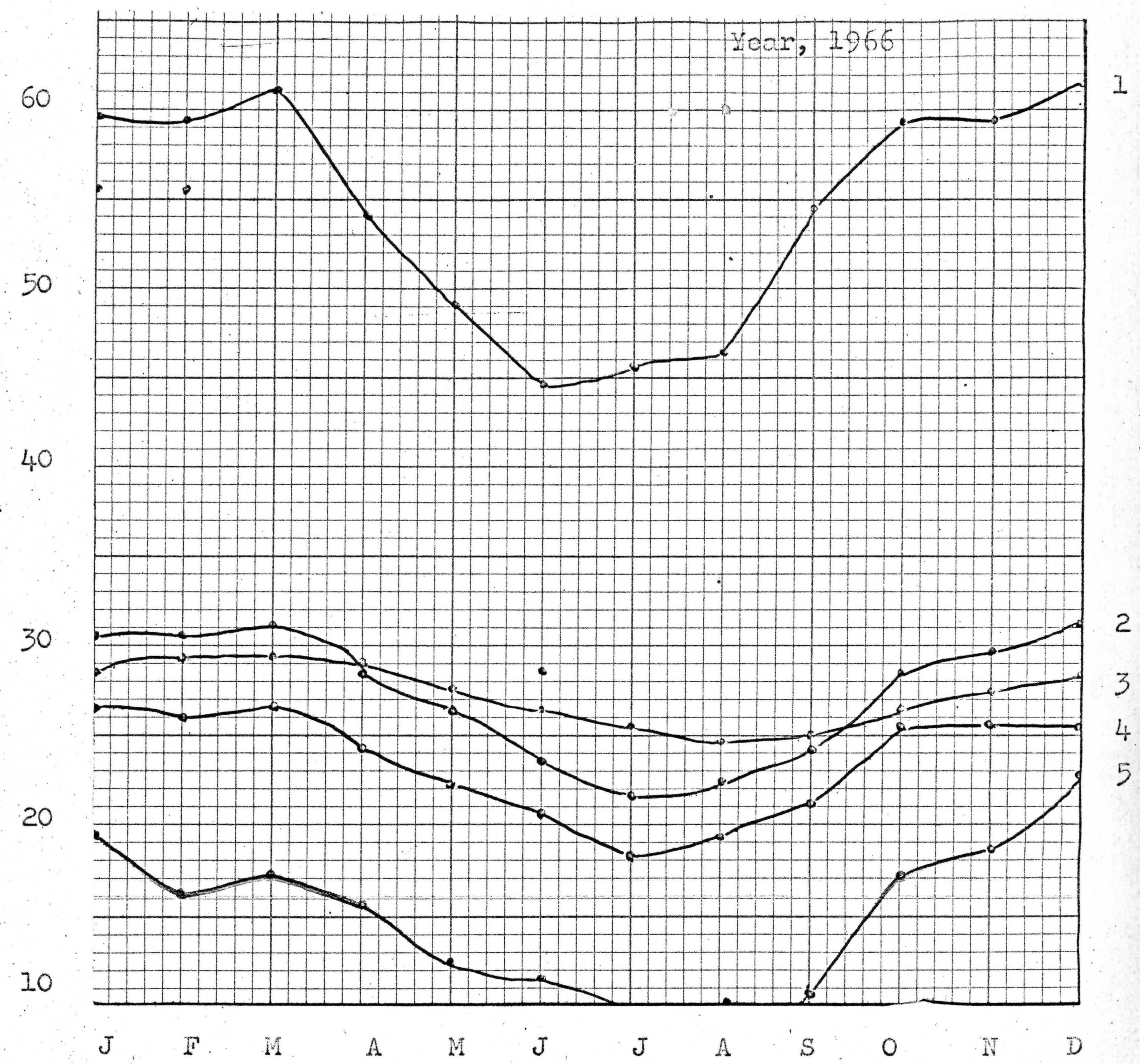
* Handbook, 1944.

\+ Records at NDRS, Gobabeb.

2 Meigs,

Diagram 8

SOIL TEMPERATURE FLUCTUATIONS AT GOBABEB



1 = Surface (1400 hrs.)
2 = 30 cms. (0800 hrs.)
3 = 120 cms. (0800 hrs.)
4 = 10 cms. (0800 hrs.)
5 = Surface (0800 hrs.)

Diagram 39

ROCK TEMPERATURE VARIATIONS AT GOBABEB

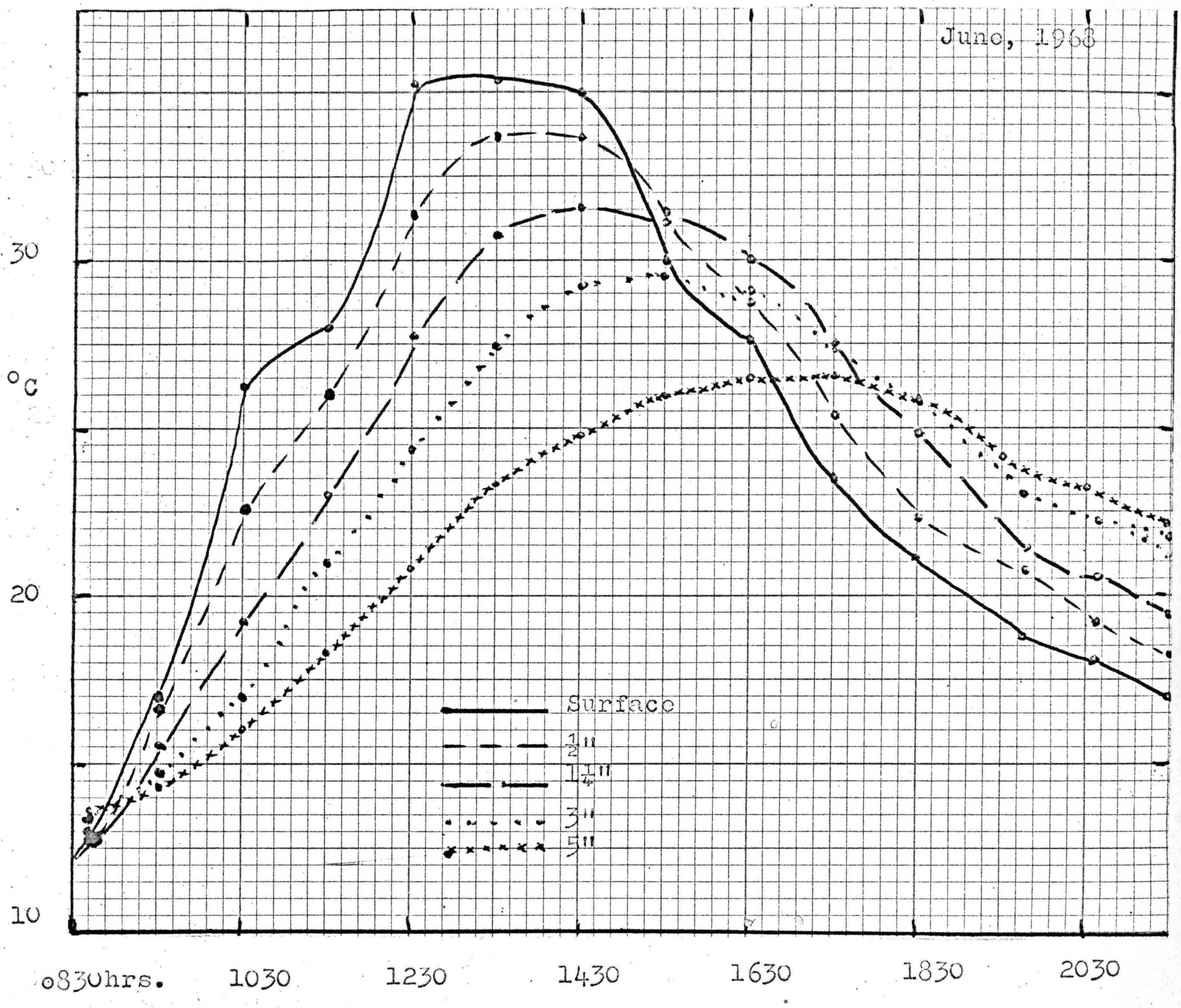
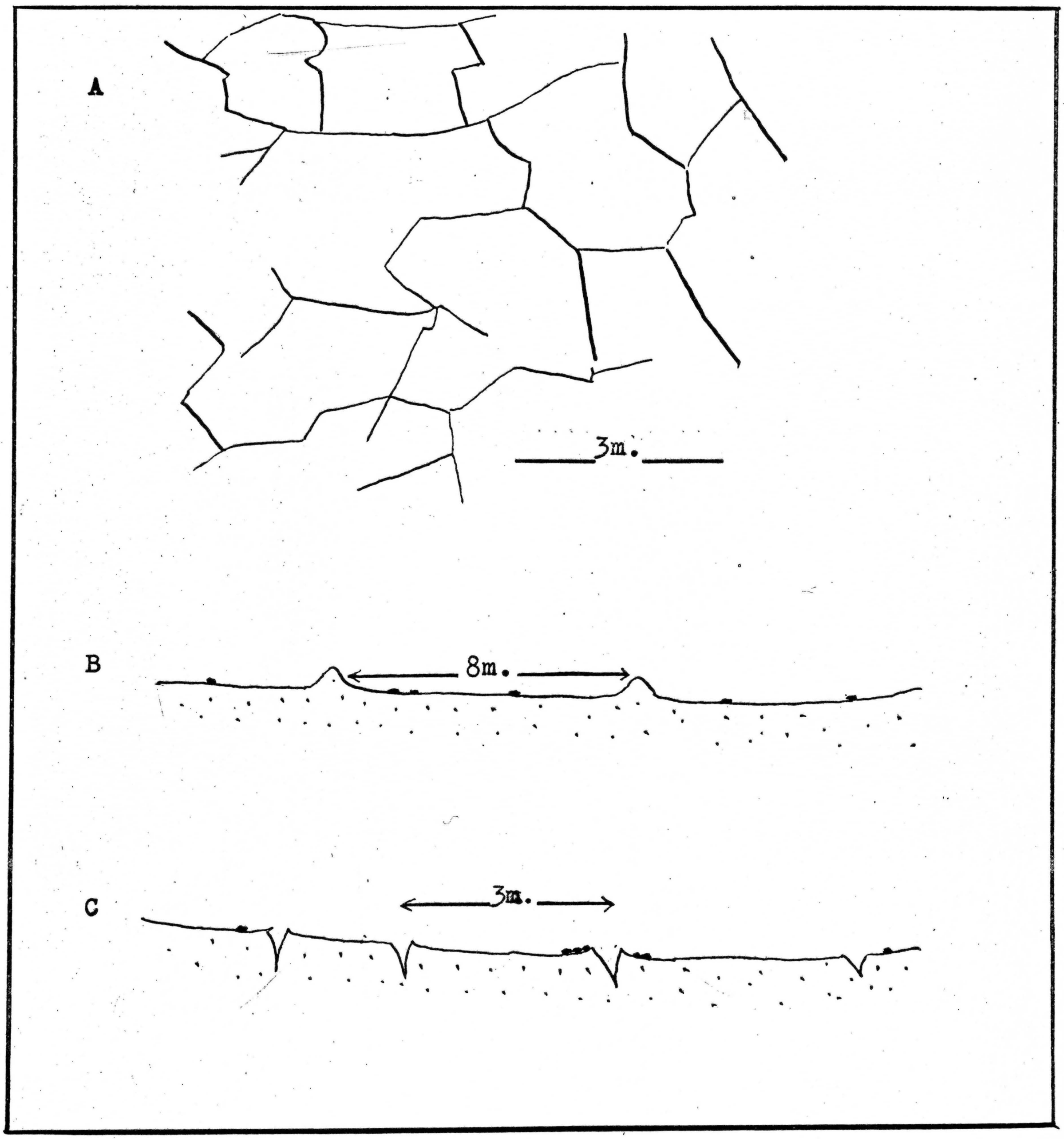


Figure 10

PATTERNED GROUND NEAR GOBABEB



A = The horizontal pattern of part of the area of polygonal structures.

B = Cross-section of polygon with raised margins

Diagram #11

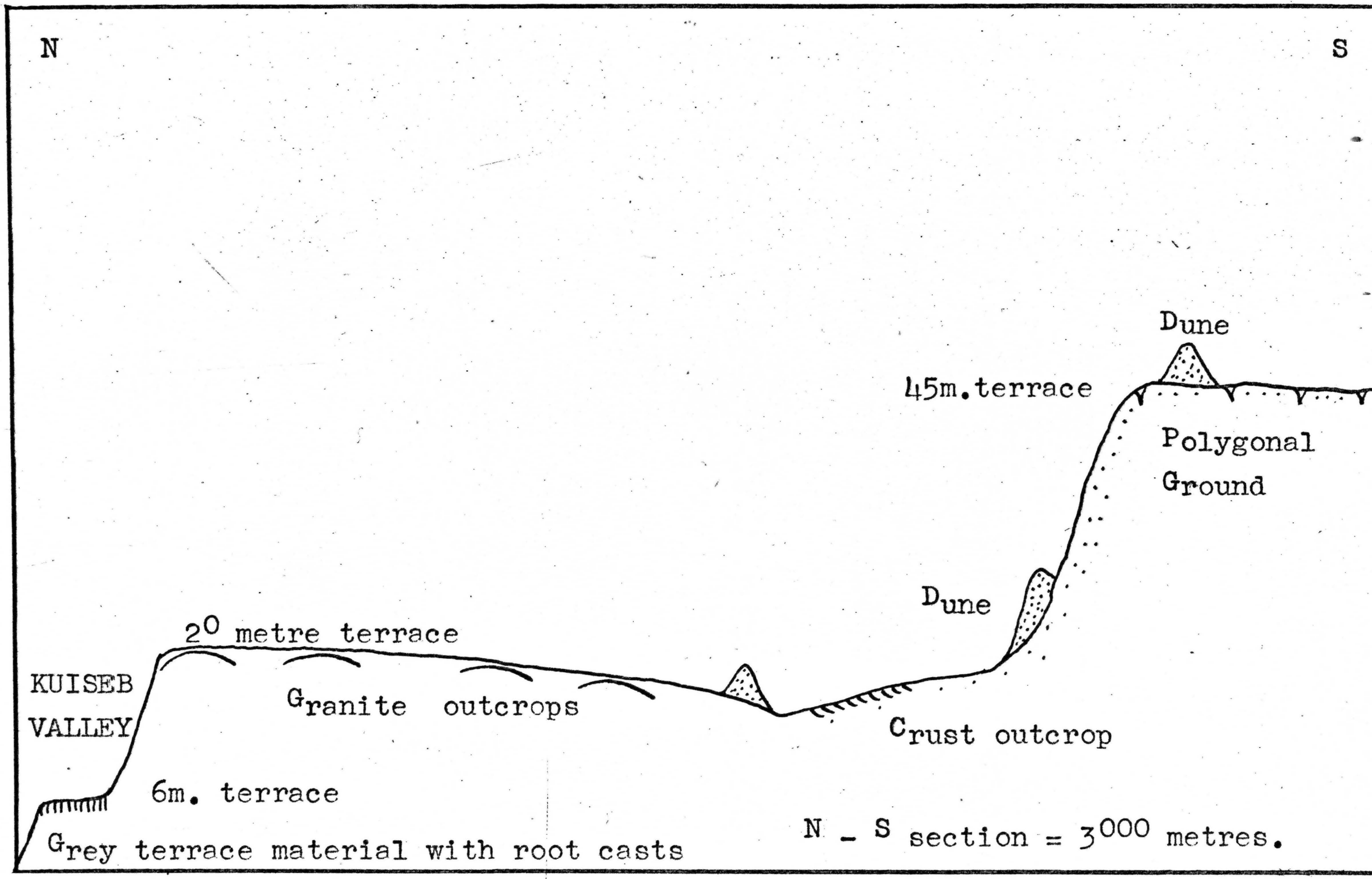
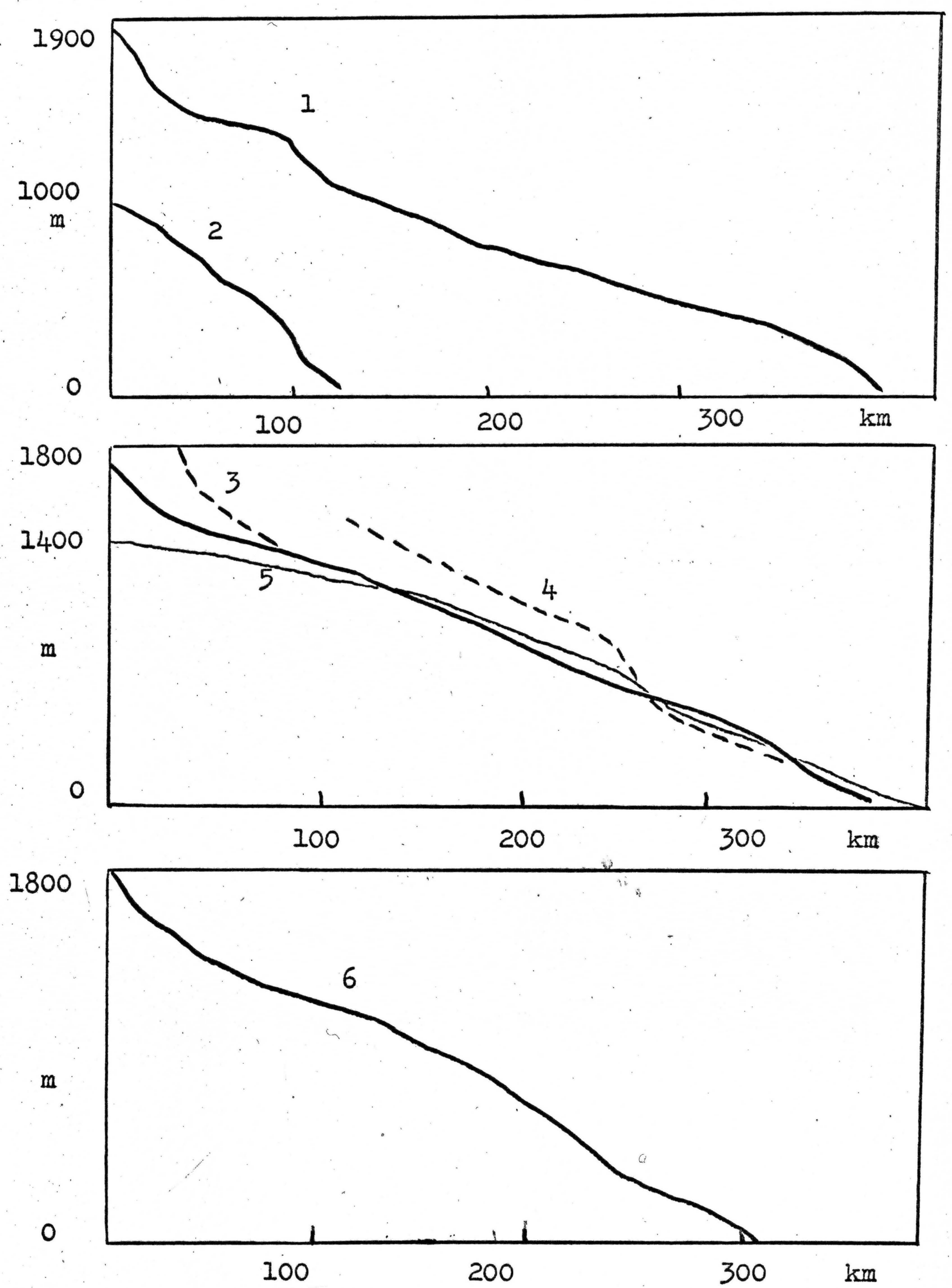

N
S
Dune
45m. terrace
Polygonal Ground
Dune
20 metre terrace
KUISEB VALLEY
Granite outcrops
Crust outcrop
6m. terrace
Grey terrace material with root casts
N - S section = 3000 metres.

Diagram 12



LONGITUDINAL PROFILES OF NAMIB RIVERS
(After Stengel, 1964, 1966)

1 = Kuiseb, 2 = Tubas, 3 = Klein Windhoek running into Swakop R., 4 = Khan, 5 = Ugab, 6 = Omaruru.

Diagram ~~5~~ 13

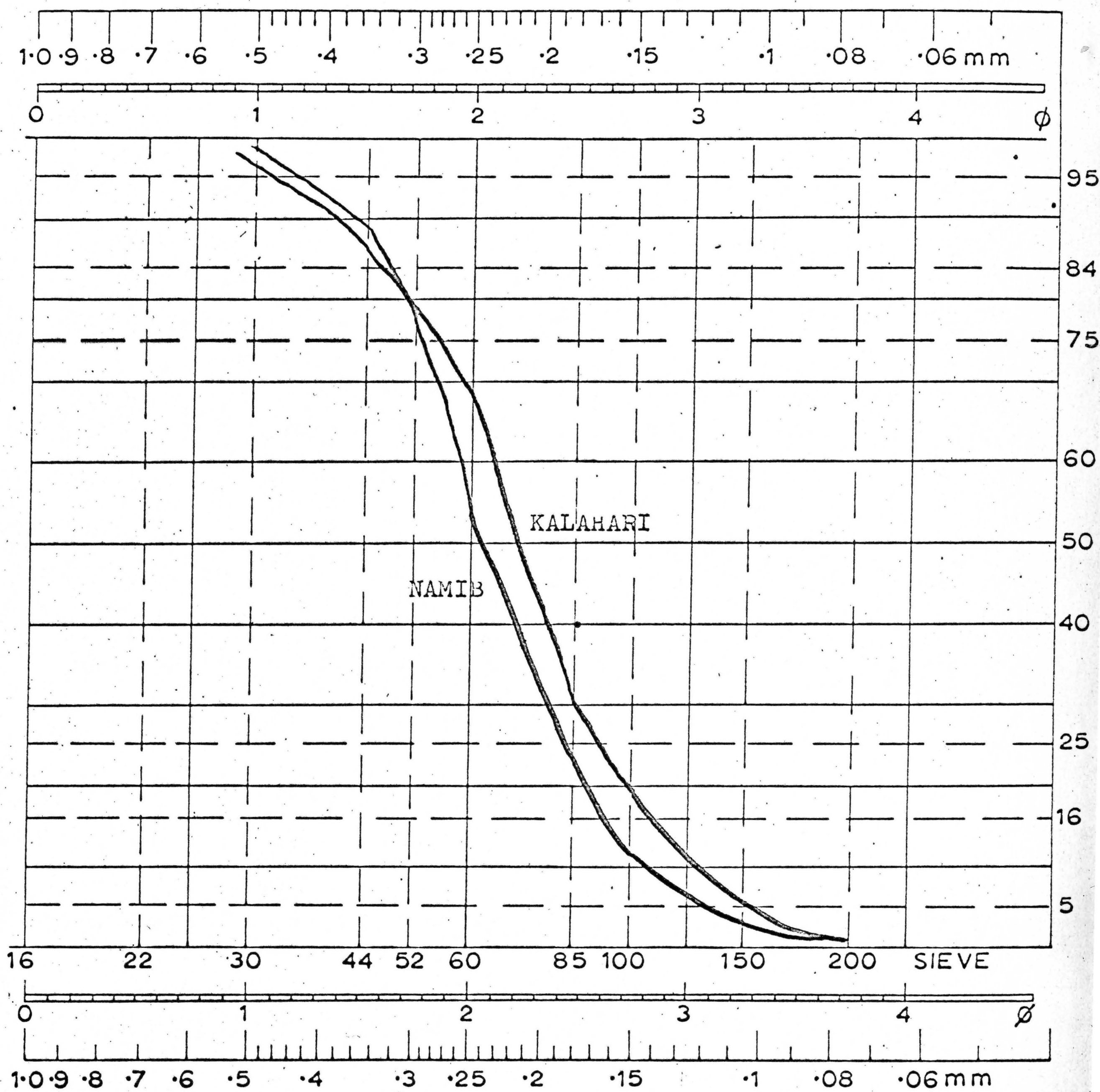
COMPARISON OF NAMIB AND KALAHARI SAND

Mean % Grain sizes			Cumulative % finer	
B.S.Sieve No.	Namib	Kalahari	Namib	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

Diagram 14



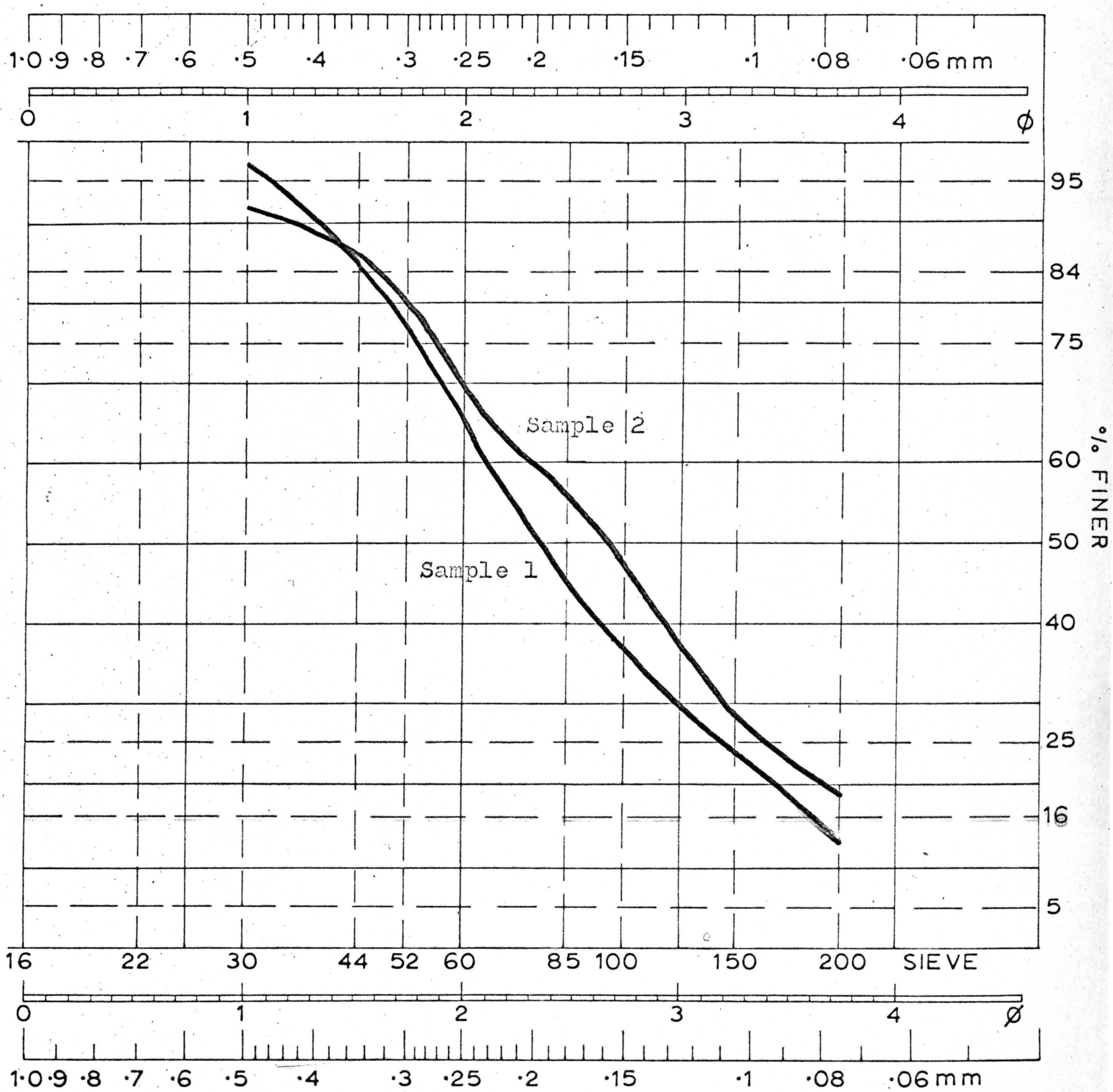
MEAN GRAIN SIZE OF KALAHARI AND NAMIB SANDS

Diagram 15

POLYGONAL GROUND PARTICLE SIZES

B.S. Sieve No.	1 %	1 Cum.%	2 %	2 Cum.%
30	2.45	97.50	7.11	92.83
44	10.66	86.84	6.22	86.61
60	20.63	66.21	17.71	68.90
85	20.80	45.41	11.71	57.19
100	7.61	37.80	9.85	47.34
150	12.99	24.81	18.30	29.04
200	11.26	13.55	10.00	19.04
Pan	13.55	-	19.04	-
% $CaCO_3$	3.55		43.83	

Diagram 16



PARTICLE SIZES OF POLYGONAL GROUND
MATERIAL FROM GOBABEB.

Diagram 17

GRAIN SIZE DISTRIBUTION FOR NAMIB
SANDS AT GOBABEB

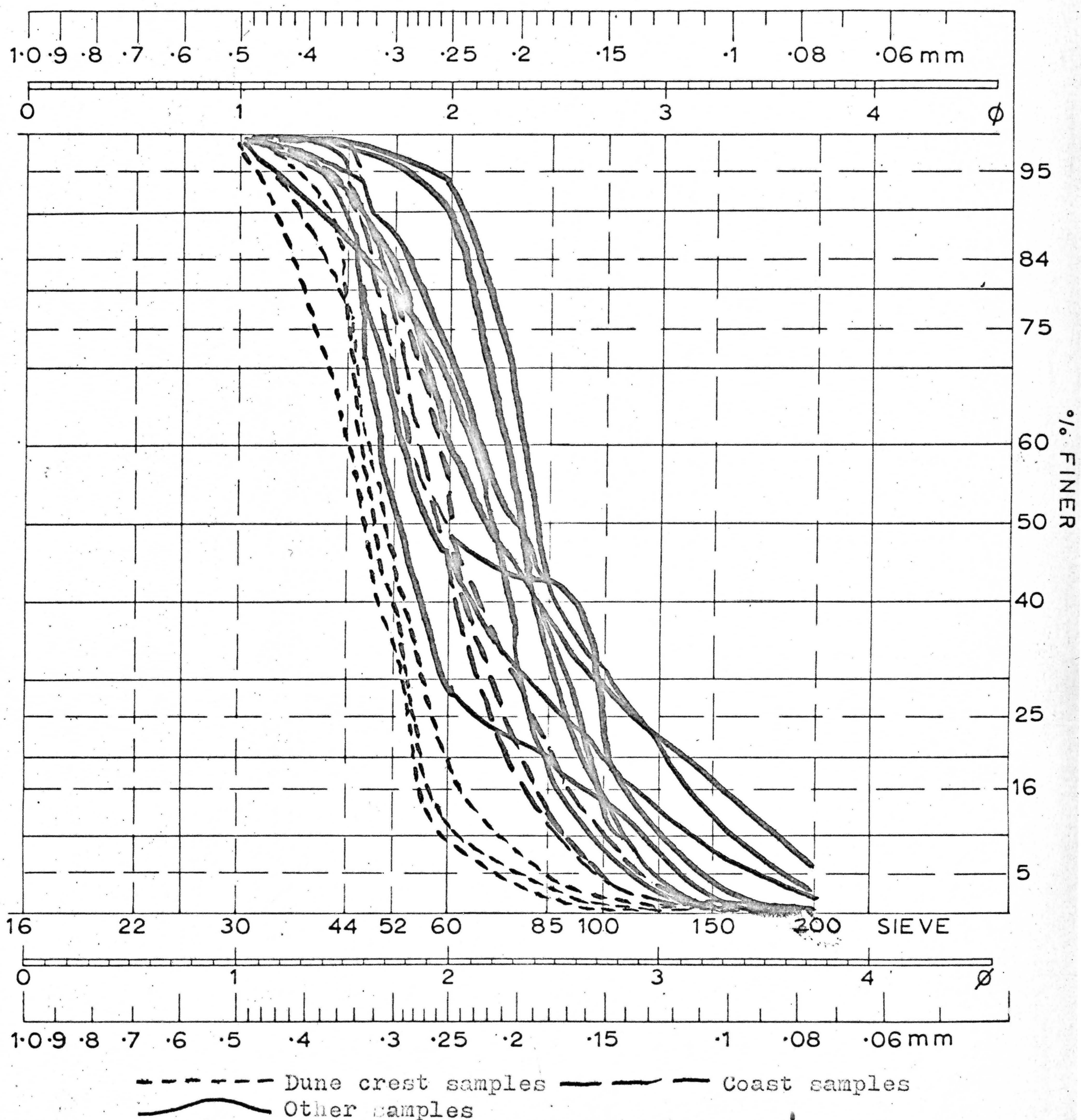
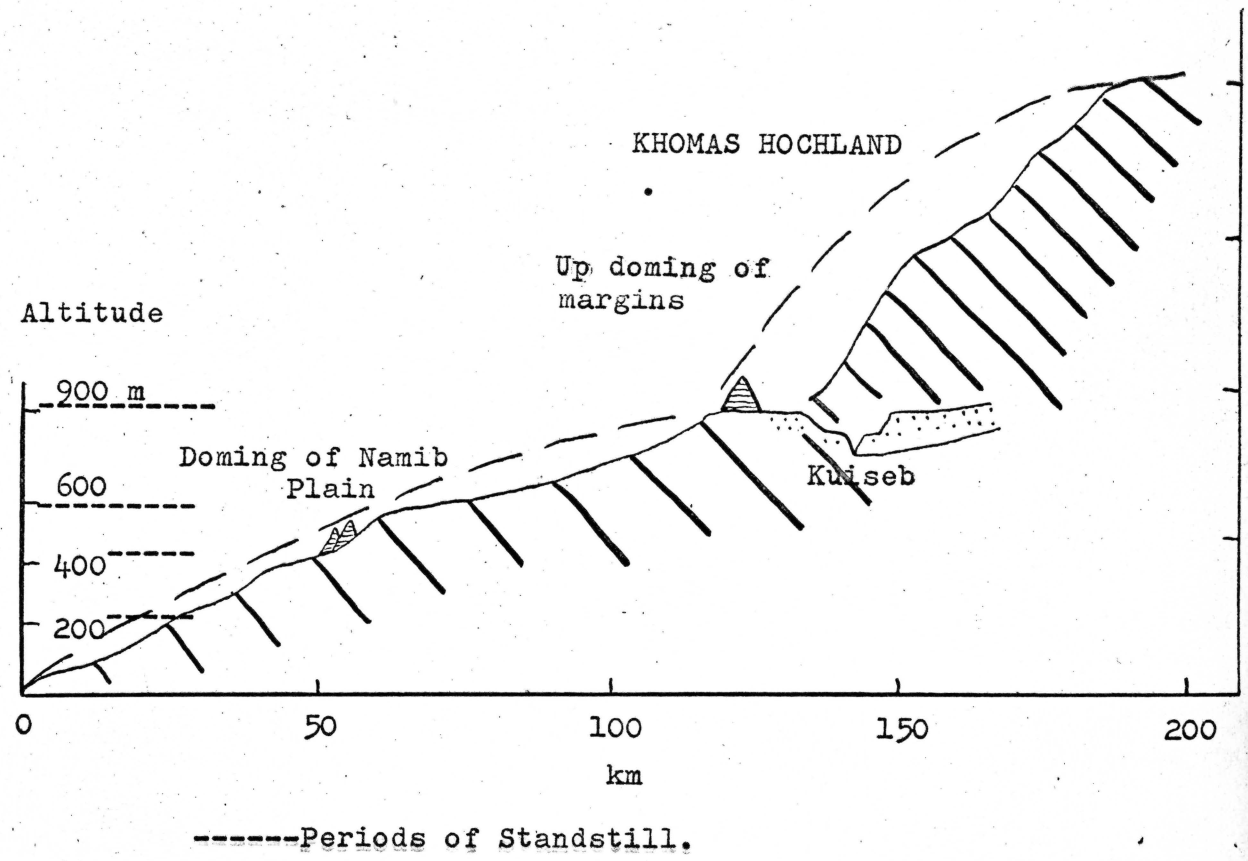


Diagram 18

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

Diagram 19



SCHEMATIC REPRESENTATION OF NAMIB SURFACES
(After Spreitzer, 1966.)

ACKNOWLEDGEMENTS

I should like to thank the Sir Henry Strakosch Memorial Trust for financial assistance in 1968, and Mr. A.T. Grove for introducing me to the Namib in 1967. I should also like to thank the South West Africa Administration for giving me permission to work in the area, and Dr. C. Koch for his unfailing assistance on my two visits to Gobabeb. This work was undertaken whilst the author was in receipt of a research studentship from the Natural Environmental Research Council of the U.K. at the Department of Geography, Cambridge.

THE GEOMORPHOLOGY OF THE CENTRAL NAMIB DESERT NEAR GOBABEB

By

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THE GEOMORPHOLOGY OF THE NAMIB NEAR GOBABEB

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 50 - 90 miles, though towards the north it narrows considerably - 47 miles near the mouth of the Cunene and only about 7 miles near Moçamedes. The desert rises to about 900 metres 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 <u>Transitional Namib</u>. North of this area, towards the Kuiseb River, he calls the <u>Middle Namib</u>. It is a tract of country with a longitudinal extent of up to 90 miles and a latitudinal extent of around 250 miles. North of the dune area is the <u>Damara</u> or <u>Northern Namib</u>. Except in the coastal belt between the Kuiseb and Swakop Rivers it is largely free of sand. Within the southern Namib the great German geologist, Kaiser (1926), attempted a geomorphic division into the <u>Trough</u> (Wannen-) <u>Namib</u>, where alternating soft and hard strata have been scoured by the wind, the <u>Plain</u> (Flächen-) <u>Namib</u>, where the sand has been deposited in the more sheltered localities to form flat surfaces, and the <u>Dune Namib</u> 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 er 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. Most of the field work was done at the Namib Desert Research Station at Gobabeb, which is about 70 miles south-west of Walvis Bay on the Kuiseb River (Diagram 1). Indeed the area in question is that covered by NASA Gemini V Colour satellite photograph S-65-45578. (NASA, 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 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.

THE GEOLOGY OF THE CENTRAL NAMIB

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

The area appears on the 1:1,000,000 Geological Map (Geological Survey of South West Africa, 1963).

Basically, the Namib Platform in the area is underlain by late Proterozoic 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 phenocrysts of orthoclase and microline felspar. The Damaran metamorphics are very variable, and include the mica schists, marble, granitic geniss, and quartzite.

Among younger intrusive rocks are black dolerite dykes. These usually show up clearly as linear ridges on air photos, 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. 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 in detail the climatic conditions of the Central Namib. This has already been done competently by Logan (1960). 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 23mm. Since 1899 the rainfall at Swakopmund has averaged 14mm. This compares with about 15mm for

Luderitz, in the southern Namib, and is similar to that for various other coastal deserts. (Meigs, 1966). Port Etienne (Mauretania) has 35 mm., Aden has 45mm., and El Refugion (Baja California) has 62mm. The rainfall in the Atacama is perhaps very slightly lower, with 1mm. being given as the mean annual rainfall for both Arica and Iquique.

The rainfall increases steadily towards the Great Escarpment, as the rainfall map shows.

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 16.5mm., but 22mm. have been recorded in a day at Goanikontes (on the Swakop River) and 740 mm. at Donkerhuk in one year (88mm. in one day). In 1934, 153mm. of rain fell at Swakopmund. The highest daily falls reported in the handbook, Weather on the Coast of Africa, (1944) are 15mm. for Walvis Bay, and 9mm. for Luderitz. In 1909 625mm. was recorded for Neuheusis, compared with only 80mm. in 1911. This variability is similar to that in parts of the South American West Coast desert. For example, Preston James (1959) writes: "At Trujillo, between 1918 and 1925, the total rainfall was only 1.4 inches; but during the month of March, 1925, a total of 15.5 inches fell, and on the three days from the 7th to the 9th rainfall was 8.9 inches."

The geomorphic significance of such rare events of high magnitude does not need stressing for an arid envioronment. Stengel (1964), for instance, has shown that the flood of 1934 at Swakopmund transported 35,000,000 m^3 of sand 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 70 miles inland. The fogs do not have the same duration as those at Port Nolloth (Republic of South Africa) - (See Weather on the Coast of Africa, 1944). At Gobabeb itself, in spite of its distance inland, fog was present at the station itself, or in the neighbourhood, on an average of 102 days for the years 1964 - 1967 inclusive. Whilst the fog only precipitated on an average of 60 days in the year, this produced a precipitation of 31mm. per annum, a figure slightly greater than the rainfall itself. Boss (quoted by Eriksson, 1958) estimated the yearly fog precipitation at Swakopmund to be 35 - 45 mm., compared with 20mm. at 40 km. inland. Daily quantities are small, though 6.5mm. has been recorded in one day at Gobabeb.

Thus, the fog brings a significant quantity of moisture into the desert, and this, coupled with its chemical characteristics, may have very considerable ecological and geomorphic significance. This point is expanded later in this report.

The winds are another very important part of the desert environment. The wind data in diagram 3 give an idea of the annual variability of the winds. At Gobabeb, east and south east winds are at a maximum frequency in winter and have mean velocities up to 21 km/hr, though actual velocities may exceed 50 km/hr. Winds from the north west show their heighest frequency in summer but have considerably lower velocities. In January diurnal variation is slight, but in the winter (July) the direction is south easterly at night until about 1000 hrs. 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 6 (Beaufort) and gales are common;. but at Walvis Bay winds af force eight are rare. Inland, at Gobabeb, velocities seem to be even lower (Diagram 6). 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." Diagram shows the greater variability of direction, which, combined with lower velocities, makes the Central Namib around Walvis Bay a very different sort of geomorphic environment to that at Luderitz.

The work of Bagnold (1941) has shown that sand flow varies as the cube of the wind velocity over and above the constant threshold velocity at which sands begin to move. The threshold velocity is generally approximately 20 km/hr. (Bagnold, 1941, p.69). The diagram constructed to show frequency and velocity of wind for each of eight directions at Gobabeb for one year stresses very clearly the importance of the relatively infrequent east and north easterly winds (Diagram 4). This topic is returned to later in the discussion of wind erosion and dune alignment and formation.

The last aspect of the climatic background is that of temperature. The whole of the coastal Namib shows a remarkable similiarity in average monthly and yearly temperatures (Diagram 7). The temperature ranges are also small.

The mean annual range betwwen the warmest and the coldest months is 9°C. at both Walvis Bay and Swakopmund (Rumney, 1968), whilst 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 the coastal areas of the Namib, though temperatures of over 40°C. have been recorded on occasions, generally in association with strong easterly 'berg' winds. In general, however, the Namib does not suffer from any very great extremes of temperature. This fact may be of some significance in terms of rock weathering.

ROCK WEATHERING

The weathering of rocks under conditions of very low rainfall has been a major theme in arid geomorphology, with much of the work having been undertaken by German scientists. Some of the early work was summarised in Walther's classic review, and there is no doubt that material from the Namib played a part in the formulation of his views. Certainly the Namib shows many 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 illustrate 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 30mm. in diameter, and up to 15mm. deep. They show no marked orientation 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 cemetation of rock so that it presents more resistant and upstanding outer surfaces, is particularly well-developed along joints in the granite. A photo from the Reasearch Station grounds is shown. It seems to be restricted to granite. 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 200mm. thick may spall off, they are frequently much thinner, and one photo shows the author holding a 20mm. slab from a granite outcrop within the dunes. 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 80cm. across as against entrances with diameters of 20cm. Such features also occur in granite south of the Brandberg Mountain. There are a large number of reports of tafoni in the literature from other parts of the world. The type-site is Corsica, whence the name, an alternative for alveolation, is derived. (Reusch, 1882; Tuckett and Bonney, 1904). They are particularly common in granitic rocks, and are well-developed in Antarctica (Prebble, 1967), and Wilhelmy (1964) cites Elba, Aruba, Peru, N.W.India, and the deserts of central Asia.

Finally, much of the granitic debris has broken down into its constituent grain sizes - granular disintegration.

These various forms, though best developed in the granites of Gobabeb, Rooikop, and Mirabib, do also occur in schistose rocks. Dolerite, on the other hand, tended to show different weathering characteristics from the other rock types. Generally it had a black, or dark red brown patina, and it tended to break down into large boulders and cobbles. In this it was different from many other rocks which showed a rather more abrupt break-down into constituent grain sizes. 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 the photo shows a reasonably common anvil-shaped weathering remnant.

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. In addition to the rillen there are small pock marks and brown staining. That the marble has undergone some solution is also evidenced by the relatively high calcium carbonate content of the gypsum crust developed on and around the Swartbank inselberg. This is discussed further in the section on Crust Formation. In places the surface of the gypsum crust itself shows minor weathering to give vermiculations - pitted and ridged micro-relief.

WEATHERING FACTORS

Insolation was given its original meaning of splitting due to the effect of expansion and cooling through solar heating by Walther (1900), and his ideas rapidly became widely applied in Egypt, Sinai, and elsewhere. Grotefeld, an early worker in the Namib (quoted by Calvert, 1916), talked 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) continues to believe in mechanical disruption of rocks, and Ollier (1963) and Greenwood (1962) 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: "Gradients in a granite structure resulting from the usual diurnal temperature changes cause internal stresses which, after numerous repititions 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 (1964) 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 'Zersplatung' (splitting), a term which allows splitting effects besides solar heating. The change in attitude has resulted from the theoretical and experimental work of Grigg and Blackwelder, and from the field work of Roth. (1965). In the context of the Namib it must be said that temperature fluctuations are not particularly severe compared with those in certain other desert areas, including the Kalahari, though sand surface temperatures at Gobabeb in 1965 showed a maximum annual range of 70.5 degrees, and the maximum diurnal range was about 50°C. The temperature variation, both annual and diurnal, falls off very rapidly beneath a thin cover of superficial material, as the graph 8 shows. I made measurements of diurnal temperature fluctuations beneath different thicknesses of granite slabs resting on sand at Gobabeb, and found the changes illustrated. These changes are less than those found by Routh in the Mohave Desert, and he showed that insolation was not a cause of quartz monzonite breakdown there. (Diagram 9)

Moreover, 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 (1950) experimental work showed that granite suffered from expansion effects caused simply by wetting.

An alternative factor involved in rock weathering in the Namib Desert may be salt crystallisation. 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 in the fog. Eriksson (1958) working on Boss's data for Swakopmund, suggested a yearly precipitation of atmospherically-derived salts of 120 kg./ha.*. 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. My own observations of fog water from drips and precipitation in the self-recording fog gauge at Gobabeb during May and June 1968, showed electrical conductivity readings of great variability, though most readings suggested a TDS content of between 100 and 1000 ppm. All samples were alkaline.

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* This compares with 130 Kg/ha for the Israel coastal tract. (Eriksson and Khunakasem, 1969).

The appreciable frequency of application of a thin spray of salt-rich water by the mist, followed by 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, as shown in a later section, is very rich in gypsum and saline crusts, and dust from these would contribute salt by direct deposition on surfaces and in cracks.

The crusts may themselves be of some importance in breaking up underlaying rocks. Soil pits dug by the author where gypsum overlies granite shows how the gypsum penetrates the granite and breaks it up. Road workings on basalt outcrops inland from Swakopmund show that gypsum veins have penetrated and split the basalt to a depth of over 20ft. Around Mirabib surface limestone (calcrete) is breaking up underlying schists, whilst on the top of Swartbank a gypsum/calcium crust is breaking up the marble. A photograph from a small gully near Gobabeb shows the exhumation of some highly weathered granite from gypsiferous terrace material.

Chemical weathering is evidenced in the Central Namib in the form of rillen and staining on marble, stainings and patinas on other types of rock, case hardening on granite, and the oversteepening at the bases of some granite inselbergs. Furthermore, Scholz mentions an iron hat on a dyke of ultrabasic dunite in the Kuiseb area. However, Logan (1960) has reported that "the cleavage faces on feldspar and mica are still untouched by weathering indicating that mechanical weathering is of sole importance." My own observations show that this is not so, and Scholz reports the presence of clay mineral formation in soils inland from Walvis Bay. 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 entirely absent. On the dolerites the lichens probably play an important role, for as Lowdermilk has suggested in America, lichens play a role in the mobilisation and deposition of Manganese and Iron to give varnished rocks. At Swartbank lichens of such species as Caloplaca elegantissima and Parmelia hottentotta (Geiss, 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. E.T.Oborn (1960) mentions that the iron content of lichens is on average 5.16 mgms per gm. of dry matter, compared with an average of only 0.30 mgms. per gm. dry matter for most land plants. Lichens are also present in large quantities on some marbles at Swartbank. The probable importance of lichens in desert weathering and crust formation has recently been discussed by Krumbein (1969).

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 crust. Scholz has already mentioned a few small polygons in some river alluvium along the Soutrivier, north west of Gobabeb, and his thesis contains plates (Abh. 47) illustrating some others. 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 United States, where they have resulted from desiccation and contraction. (Neal, 1965; Christiansen, 1963; Willden and Mabey, 1961; Long, 1943; and Neal and Motts, 1967.) Some of these polygons may be as much as 300 metres in diameter. Desert clay soil polygons and patterned ground are also well known. Alimen (1953) reports them from North Africa, and Ollier reports them from South Australia (1966).

However, the gest 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.

Like most natural polygonal features, such as some tundra soils, columner structures in basalt, and mud cracks (see D'Arcy Thompson (1961)) the polygons are random orthogonal polygons (Lachenbruch, 1962) with a tendency towards hexagonal and pentagonal shapes. Because of imperfect development of some fissures the ideal hexagonal shape is not always reached at Gobabeb, and even in cohesive and homogeneous clay this is frequently the case. Examination of several mud-crack photographs from various sources resulted in an average of about 5.10 sides being found for a sample of 200 polygons. With the rather variable material in the Gobabeb crust it is not surprising that perfect hexagons do not develop. However, stripes or elongated polygons do not appear to be common. Some of the polygons have internal dimensions of upto 20 m. across, though between 8 and 9 m. is the average size. The polygons show various forms: the largest polygons have a raised margin of whiter calcareous gypcrete (calcium carbonate content about 25-40 %) which may have a relief of 40 cm. (See photo). Other polygons are marked not by ridges but by depressions along fissures and may or may not have upturned edges (see diagram 10). Other polygons may have very slightly raised middles, with pebbles forming rings around the dome, though this form is rare in its perfect form.

The polygons occur on the flat surface of the gypsum-calcrete terrace which lies at about 45m. above the south bank of the Kuiseb. The terrace extends well into the dune area. The crust is many feet deep, with almost the whole terrace being cemented to a greater or lesser degree. The bulk of the cemented material is of sand size (see grain size diagram) and is capped by, and contains some, well-rounded, wind polished, fluvial pebbles, (diagrams 15, 16).

Because of the minimal rainfall of the area it is difficult to attribute the polygons to wetting 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.

Both topographic position, and relative lack of clay minerals, seem to exclude any idea that they are formed by playa desiccation or by expansion and contraction of clays. These have been the two favourite explanations for patterned ground in other arid lands. Any explanation through frost action, akin to that occurring in tundra envioronments, is ruled out by the present almost complete absence of frost. Evidence from elsewhere in South West Africa does not suggest a particularly cold period in the period since the formation of the terrace upon which the polygons rest (probably Upper Pleistocene). The raised nature and different characteristics 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 has yet to be fully explored. Thus, unless there was some increase in humidity since the terrace was formed, it is difficult to give any satisfactory explanation for the polygons. It is particularly difficult to explain the great size of the polygons, though the thickness of the crust may be one possible reason. Thin crusts can generally sustain only small polygons, though this varies very greatly with the physical properties of the materials involved.

Another sort of patterned ground is caused by the trapping of sand by scattered masses of vegetation to give pimpled ground. This is particularly evident on air photos of the valley fringes and the coastal zone around Swakopmund. Acanthosicyos horrida Welw. and Citrullus ecirrhosus Cogn (both Cucurbitaceae) are responsible for such mounds, but Salvadora persica gives some of the clearest examples. (See photo). The mounds, which show similarity to the phreatophyte mounds around playas in the United States, average about 50m. in diameter, and are generally about 3 - 4 m. in height. Some of the pimpled ground of the Western Cape, in the Malmesbury area, locally called heuveltjies, may be largely relict mounds formed under more arid conditions.

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 4m. 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 calcium carbonate. Martin (1963) describes the location of some of the higher grade deposits, and believes that the gypsum crusts result 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 (for example, north east Africa) the present author is not sure. In the vicinity of marble ridges and inselbergs the gypsum contains above average quantities of $CaCO_3$, and 3 samples from Swartbank had $CaCO_3$ contents of 44.5%, 21.6% and 35.14%, thus showing the local effects of the highly calcareous marble (96% $CaCO_3$). 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%.

No particularly marked change is evident in the composition and character of the crusts until one is about 60 - 70 miles 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 particularly well developed in the small, shallow drainage lines running from inselbergs, probably because of the local presence there at certain times of more soil moisture. This particular calcrete may for that reason have no particular age or palaeoclimatic significance. It is seldom more than a meter 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 rims to give a feature of marked geomorphic importance. The spread of the calcification process has led to the slight disruption and doming of the underlying rocks, and has also tended to form in circular masses. Such 'boils' are seldom more than 3 - 4 m. across and do not, therefore, compare in size with 'calcrete anticlines' described by Jennings and Sweeting (1962) for Western Australia, and also known in the clacrete surrounding the Etosha Pan.

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 has described Upper Pleistocene terraces at 40 ft. above present drainage level. Such low, calcareous terraces also line the Tubas.

THE KUISEB RIVER

The Kuiseb rises in the Khomas Hochland near Windhoek, and, as a result of the relatively high rainfall and runoff in that area, is the first major river to reach the Atlantic north of the Orange River. 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 wadis, like the Sout Rivier bring in some flow from the north 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 the other rivers of the north and central Namib, the long profile of the river shows a tendency towards convexity, rather than the concavity characteristic of most rivers. (See diagram 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, 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.

The river 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. Speitzer (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 diagram II. 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 maintaining 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 (Vegter, 1953) 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. It seems possible that they were formed in the not too distant past by the ponding up of the Kuiseb. If they were of any great age one would suspect they would have become cemented like the Upper Pleistocene terraces along the river not very far to the west. However, the river bed is now incised deeply into bedrock, and the gorge into which the sediments were deposited must be of considerable age. In many places too, especially to the east of Gobabeb, the incision of the stream bed suggests that a shift to the north has not taken place in the very recent past.

The reason why the dunes stop so abruptly at the Kuiseb is that such big dunes 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 lesser influence of river floods at the mouth, and 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. In addition rare northerly winds of high velocity would play a role in keeping the dunes from crossing the River. A further possibility is that the dunes have only recently reached the River, and that the northern boundary of the dunes co-incides with the Kuiseb purely fortuitously. There is some support for this idea from the eastern part of the dunefield, for a German geological map of 1912 shows a road or track running on the south side of the Kuiseb as far west as Natap. (Range, 1912).

Towards the Kuiseb Gorge north bank, tributaries of the Kuiseb, like those of the Swakop, have cut back into the Damara rocks, largely schists, to give a badlands type of scenery. This has been termed the 'Gramadullas'.

Whilst some of the gullies may be the result of past wetter periods, it seems likely that infrequent storms of high intensity could, in the course of time, erode the landscape in this way. The Swakop is lined by a much more incised series of gullies in its lower course than is the Kuiseb, and, as the satellite photo clearly shows, is more constricted by banks.

THE DUNES OF THE NAMIB

The dunes of the Namib are reputed to be the biggest in the World, and examination of staellite photos taken by the astronauts of Gemini 4 and Gemini V suggests a broad similarity with those of the Empty Quarter of Arabia (NASA, 1967, pp. 23, 47, 137) and with those of southern Algeria (p. 154). They are basically linear dunes averaging near Gobabeb about 80 - 100 m in height. Near the Sossus Vlei, however, they have been reported as reaching 250 or 275 m in height above the surrounding plain (Jaeger, 1939, p. 19). The Sossus is one of the three major vleis - the other two being the Tsondab and Kuichab Vleis - which fails to breach the massive dunes. However, the staellite photo of the Namib does suggest some discontinuity in the dunes to the west of the Tsondab vlei.

The main trend of the dunes is approximately from north to south, and it is probable that easterly winds are responsible for this trend as they are dominant at velocities greater than the threshold velocity required for the movement of sand. Near the coast, as the satellite photo shows, some dunes trend approximately NE to SW, and this probably results from the relatively higher velocities nearer the coast which enable the very frequent south westerly winds to play a greater role in sand movement than they do further inland where velocities appear to be less. (Diagram 6)

Random measurements of 50 maximum dune slope angles shows the average lee (steep) slope to be just under 32°, and the average windward slope to be 25°.

These dunes are markely bigger 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. In the western Kalahari, near Koes in South West Africa, the dunes average only

80 feet (25 m.) and have inter-dune streets only 300 m. across, campared with 1000 - 1500 metres in the Namib. However, the spacing of some dunes near the Tsodilo hills in Botswana, together with their width, suggests that they may at one time have had a similar size to those at Gobabeb. The characteristics of Kalahari and Namib sand are generally similar. (See diagram 14).

The cumulative percent grain size diagram and tables shows the nature of the sand which forms the dunes in the Central Namib. The grain sizes lie between 0.5 mm. and 0.07 mm., so that the sand can be classed as medium, fine and very fine under the Wentworth Classification. Though the sample is not big enough to allow any firm assertions, the crests of the linear ridges seem to have slightly coarser sizes than sand taken from the slopes of the dunes.

Inland from the coast, behind the coastal dunes between Swakopmund and Walvis Bay (Samples, N/A18, N/A19, N/A17), 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 Kahan Mountain and Rössing Mountain. The sand accumulation from the easterly berg winds at Rössing extends over 300 ft. (90m.) 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 of weathered schistose rock from the steep rock slope above. (Diagram 18)

THE INSELBERGS AND THE PLAINS

Spreitzer (1966) has reviewed the chronology of denudation in the Central Namib. (Diagram 19) He suggests that the inclined plane of the Namib, which rises to 900 - 1200m., 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 (see photo). 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 it is a pre-Permo-Triassic surface (personal communication to Logan, 1960) that has been re-exposed from beneath younger beds, and in contrast, Kaiser (quoted by Gevers, 1936) suggested it was formed in a Cretaceous humid period. The general consensus of opinion, as reviewed by Logan, 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 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 envioronment of breaking down abruptly from boulder size to constituent grain

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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 role 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 accumulations 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 vegetation-less area.

Wind seems to be relatively unimportant in the shaping of slopes in the Central Namib, though one does see some minor undercutting of rocks. Gypsum crusts protect much of the area from deflation and there are not the alternating 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 Korrasions-Landschaft der Rücken und Kuppen' in the Dolomite of the Nama system. Moreover, in the Central Namib, as Gevers remarked, 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 sandstein 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 coarse 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, particularly in the area to the south of Kenhard (C.P.). Much of the material forming these pavements is highly polished, whilst on the under sides quartzitic pebbles may be stained by green window algae.

QUATERNARY CLIMATIC CHANGE IN THE CENTRAL NAMIB

The whole history of climatic change in Southern Africa is most uncertain, and the old chronology of Van Riet Lowe et al based on the Vaal River Terrace Sequence, which for so long acted as a base, has been convincingly shown to be inadequate (Partridge and Brink, 1967). However, that there was a marked degree of climatic change in the Kalahari is not in doubt, 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 rivers of the Namib, which have their sources in the highlands of South West Africa, would essentially be external evidence. However, Korn and Martin have suggested a widespread Middle Stone Age pluvial for South West Africa, and in the Naukluft area (as reported by Söhnge and Van Riet Lowe) have suggested a pluvial period coinciding with the beginning of the Pleistocene. Martin and Mason, (1954) from a tufa deposit in Phillips Cave, Erongo Mountains, on the edge of the Namib, have suggested a slightly higher rainfall at one time during the formation of Bed II. Surface limestone, which probably needs a higher rainfall than that at present in the Namib, is widespread, but much of it may be Tertiary (Pliocene) in age, and the dating of the rest is uncertain. Smith suggest that a 40ft. calcreted terrace in the Swakop valley is Upper Pleistocene in age. The fact that the Tubas River, unlike those rivers with their sources in the highlands, has been unable to penetrate the dunes or to dissect its course into the Namib Plain, suggests that there was insufficient rainfall within the confines of the Namib itself.

There are two further lines of evidence which point to moister conditions during the Pleistocene in the central Namib.

At the Cape Town Museum, Carrington is working on the fauna of the raised beaches along the coast of South Africa and South West Africa. He has found evidence of a warm water fauna in some of the raised beach material. The fauna indicates warmer temperatures in the Benguella Current, and this would almost certainly lead to higher rainfall totals. This confirms the earlier work of Haughton (1932).

Secondly, Scholz (1968) has described a buried fossil, red-brown soil from just east of the Kuiseb near Gobabeb. This fossil soil appears below the gypsum crust and is characteristic of alternating moist and warm climates. The soil has the following profile (Scholz, p. 102):

0 - 3 cm. A: Ochre brown, gritty sand with incoherent fabric, covered by a loose layer of quartz grit.

3 - 7 cm. Ca_1 : As above, but containing $CaCO_3$

7 - 30 cm. Ca_2 : Brownish-yellow, somewhat loamy sand, rich in $CaCO_3$, with polyhedral fabric and a loose network of roots.

30 - 40 cm. Y : Yellowish-white, very coherent gypsum crust free of $CaCO_3$

40 - 80 cm. fCY_1 : Reddish-brown clay, partly consolidated by gypsum.

80 - 120+ cm. fCY_2 : Reddish-brown clay-gypsum crust with scattered white specks.

The geological and geomorphic evidence for the Namib is therefore not very conclusive. The archaeological evidence is in a similar state. The ecological evidence, on the other hand, does not suggest any great degree of climatic change, for the Central Namib dunes have a uniquely endemic fauna, which is extraordinarily specialised.

Koch (1960) wrote: "The limited exploration so far carried out shows that the endemic tribes, genera, and species far out number those found in other deserts of the world and in no other desert 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 adaptation and endemism of the Namib fauna.

If the Namib has indeed undergone only minor climatic change it makes it of great importance for the study of 'true' desert geomorphology. Most other deserts, including the Atacama, seem to have undergone marked climatic change in the Pleistocene.

REFERENCES

Alimen H. (1953), Polygones de cailloux sur les sols desetiques, Colloques Internationaux du Centre National de la recherche scientifique XXXV, Actions aeoliennes, Phenomenes d'evaporation et D'Hydrologie superficielle dans les regions arides, Alger, 1951.

Bagnold R.A. (1941), The Physics of Blown Sand and Desert Dunes, London.

Birot P. (1954), Désagrétion des Roches cristallines sous l'action des sels, C.R.Acad. des Sciences de Paris, 238 (10) 1145-6.

Birot P. (1968), The Cycle of Erosion in different climates, trans. by C.I.Jackson and K.M.Clayton, London. 144 pp.

Blackwelder E. (1933), The Insolation Hypothesis of rock weathering, American Journal of Science, 26, 97-113.

Butzer K.W. and Hansen C.L. (1968), Desert and River in Nubia, Wisconsin 562 pp.

Calvert A.F. (1916), The German African Empire, Laurie, London,

Cloos H. (1954), Conversation with the Earth, trans. by E.B.Garside, London.

Clifford (1967), The Damaran Episode in the Upper Proterozoic-Lower Palaeozoic Structural History of Southern Africa, Geological Society of America Special Paper No. 92, New York.

Christiansen F.W. (1963), Polygonal Fracture and Fold Systems in the Salt Crust, Great Salt Lake Desert, Utah, Science, 139, 607-9.

Commonwealth Bureau of Soils (1966), Bibliography on Desert Pavement, Bibliography 980, (Mimeo), Harpenden, U.K.

Eriksson E. (1958), The Chemical Climate and Saline Soils in the Arid Zone, UNESCO Arid Zone Research, X Climatology, Reviews of Research, 147-180.

Eriksson E. and Khunakasem V. (1969), Chloride concentration in ground water, recharge rate, and rate of deposition of chloride in the coastal plain of Israel, Journal of Hydrology, 7 (2), 178-97.

Geiss W., (1962), Some notes on the Vegetation of the Namib Desert, Scientific Papers of the Namib Desert Research Station, VIII (3) 35pp.

Gevers T.W. (1936), The morphology of Western Damaraland and the adjoining Namib Desert of South West Africa, South African Geographical Journal, 19, 61-79.

Greenwood J.E.G.W. (1963) Rock Weathering in Relation to the Interpretation of Igneous and Metamorphic Rocks in Arid Regions.

Griggs D.T. (1936), The factor of fatigue in rock exfoliation, Journal of Geology, 44, 781-96.

Haughton S.H. (1932), Transactions Geological Society of South Africa, 34, p.19.

Hockmann A. and Kessler D.W. (1950), Thermal and Moisture Expansion Studies of Some domestic granites, U.S. Bureau of Standards Journal of Research 44, 395-410.

Jaegar F. (1939) Die Trockenseen der erde, Petermanns Mitteilungen, Erganzungsheft 236, 159 pp.

James P.E. (1959), Latin America. Cassell, London

Jennings J.E. and Seeting M.M., (1962), Caliche Pseudo-anticlines in the Fitzroy Basin, W.Australia, American Journal of Science 259, 634-639.

Kaiser E. (1923), Kaolinisierung und verkieselung als verwitterungs-vorgänge in der Namibwüste Südwestafrikas, Zeit. fur Krystallographie 58 125-46.

Kaiser E., (1926), Die Diamantwüste Sudwestafrikas, 2 Bde., Berlin.

Koch C. (1960), The tenebrionid Beetles of South West Africa, Bull. South African Museums Assn. 7 (4) 73-85.

Koch C. (1961), Some aspects of abundant life in the vegetationless sand of the Namib Desert dunes, Journal of the South West Af. Sci. Soc. XV, 1961, 9-92.

Krumbein W.E. (1969), Uber den einfluss der mikroflora auf die exogene dynamik (Verwitterung und Krustenbildung), Geol. Rundschau 58 (2), 333-62.

Lachenbruch A.H. (1962), Mechanics of Thermal Contraction Cracks and Ice-Wedge Polygons in Permafrost, Geological Society of America Special Papaer, 70, 69 pp., New York.

Lang W.B. (1943), Science 98 (1943), 583-584. Gigantic Drying Cracks in Animas Valley, New Mexico.

Leopold L.B., Wolman M.G., and Miller J.P., (1964), Fluvial Processes in Geomorphology, Freeman, San Francisco.

Logan R.F. (1960), The Central Namib Desert, South West Africa, Nat. Ac. Sci. Nat. Res. Council, Washington D.C.

Martin H. (1963), Gypsum Deposits of South West Africa, Trans. Geol. Soc. S.Africa, LXVI.

Martin H. and Mason R. (1954), Test Trench in the Phillips Cave, Ameib, Erongo Mts., S.W.A., S.African Archaeol. Bull. 36 (9), 148-51.

Martin H. (1965), The Precambrian in South West Africa, Cape Town.

Martin H. (1965), A Bibliography of Geological and Allied Subjects, South West Africa; Bulletin Precambrian Research Unit (Chamber of Mines) Cape Town Dept. of Geol., 1.

Martin H. (with H. Korn), 1955, The Pleistocene in S.W.A., Proc. of 3rd. Pan African Conference on Prehistory, p. 14.

Meckelin W., (1959) Forschungen in der Zentralen Sahara, George Westermann Verlag.

Meiggs P. (1966), Coastal Deserts of the World, UNESCO Arid Lands,

Merensky H. (1909), The Diamond Depositis of Lüderitzland, Trans. Geol. Soc. S.Africa XII, p.13.

National Aeronautics and Space Administration (1967) Satellite photos from Gemini 3, 4 and 5.

Neal J.T., Giant Desiccation Polygons of Great Lake Playas, Air Force Cambridge Research Lab. Office of aerospace research, USAF environmental research papers, 123, (1965), 20 pp.

Oborn E.T. (1960), The Iron Content of Selected Water and Land Plants U.S.Geol. Surv. Water Supply Paper, 1459 - G.

Ollier C.D. (1963), American Journal of Science 261, 376-81.

Ollier C.D. (1966), Desert Gilgai, Nature 212 (5062), 581-3.

Partridge T.C. and Brink A., (1967) Gravels and Terraces of the Lower Vaal River Basin, South African Geographical Journal, XLIV, 21 - 38.

Prebble M., (1967), Cavernous Weathering in the Taylor Dry Valley Victoria Land, Antartica, Nature 216 (5121), p. 1194.

Range P. (1912), Geologie der Deutschen Namalandes, Beitr. fur Geol. Erforschung der Deutsch Schutz gebiet.2.

Reusch H.H. (1882), Geologie de la Corse, Bull. Soc. de Geol. de France, XI, 62-67.

Roth E.S. (1965), Temperature and Water as Factors in Desert Weathering. J. Geology, 73, p.454

Rumney G.R. (1968), Climatology and the World's climates, Macmillan, New York and London.

Schattner I. (1961), Weathering Phenomena in the Crystalline of the Sinai in the light of current notions, Bull. Res. Council of Israel, 10 G.

Scholz H. (1963), Studien über die Bodenbildung zwischen Rehboth und Walvis Bay, Dissertation Dr. Agr. Bonn.

Scholz H. (1968), Die Boden der Wuste Namib/Südwestafrika, Zeits. fur Pflanzernahrung und Bodekunde, 119 (2), 91 - 107.

Smith D.A.M., (1962), The Geology of the Area around the Khan and Swakop River in S.W.A., Memoir 3, S.W.A. Series, Geological Survey S.Africa

Sparks B.W. (1960), Geomorphology, Longmans, London.

Stengel H.W. (1964) and (1960), The Rivers of the Namib and their Discharge into the Atlantic, Scientific Papers of the Namib Desert Research Station, No. 22, and No. 30.

Spreitzer H. (1966), Beobachtungen zur Geomorphologie der Zentralen Namib und ihrer Randgebiete, Journal S.W.A. Scientific Society, XX.

Thompson W. D'Arcy, (1961), On Growth and Form (abridged edn.), Cambridge.

Tuckett F. and T.G.Bonney (1904), Eroded Rocks in Corsica, Geological Magazine, Decade V, Vol 1. No. 482.

Van Riet Lowe C. and Sohnge P.H., The Geology and Archaeology of the Vaal River Basin, Memoir 35, Union of South Africa Dept. of Mines, Geological Survey.

Vegter J.R. (1953) Underground Water Supplies in the Crystalline Complex of the Kenhardt District C.P. and the Water supply of Walvis Bay, MSc Thesis, Faculty of Science, University of Pretoria.

Walther J. (1900 and 1924), Das Gesetz der Wüstenbildung in Gegenwart und Vorzeit, Leipzig.

Weather on the Coast of Southern Africa, (1944) Royal Navy and Royal South African Airforce Meteorological handbook.

Wellington J.H. (1955) Southern Africa, A Geographical Study, 2 Vols., Cambridge.

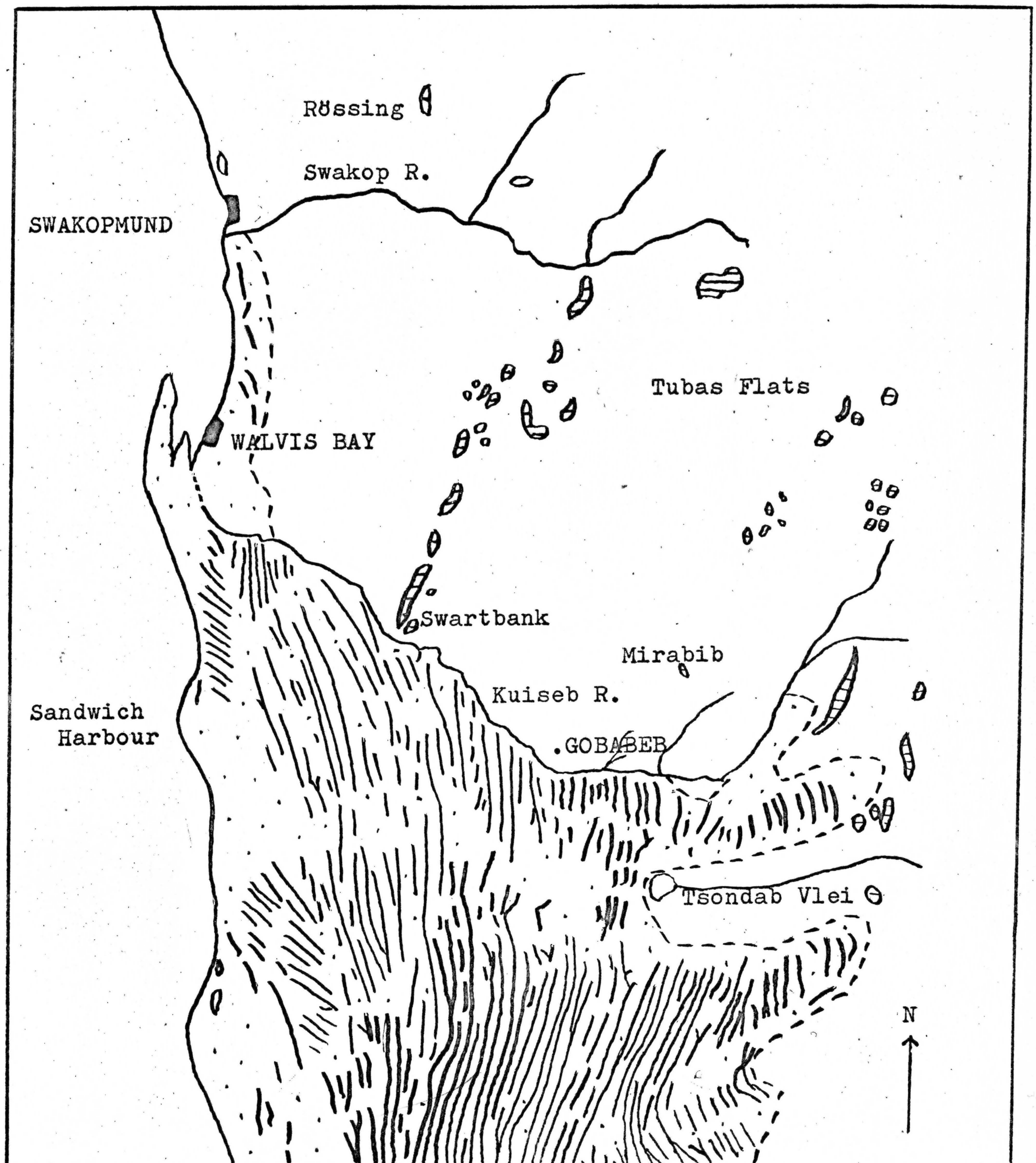
Wellington J.H. (1967), South West Africa and the Human Issues, Oxford.

Wellman H. and Wilson T. (1965), Salt Weathering, a neglected geological erosive agent in coastal and arid environments, Nature, 205, 1097-8

Wilhelmy H. (1964), Cavernous rock surfaces (Tafoni) in semi arid and arid climates. Pakistan Geographical Review 19 (2), 9 - 13

Willden and Mabey D.R. (1961), Giant desiccation fissures on the Black Rock and Smoke Creek Deserts, Nevada, Science 133, 1359-60.

Diagram 1



THE CENTRAL NAMIB

Fig. 3

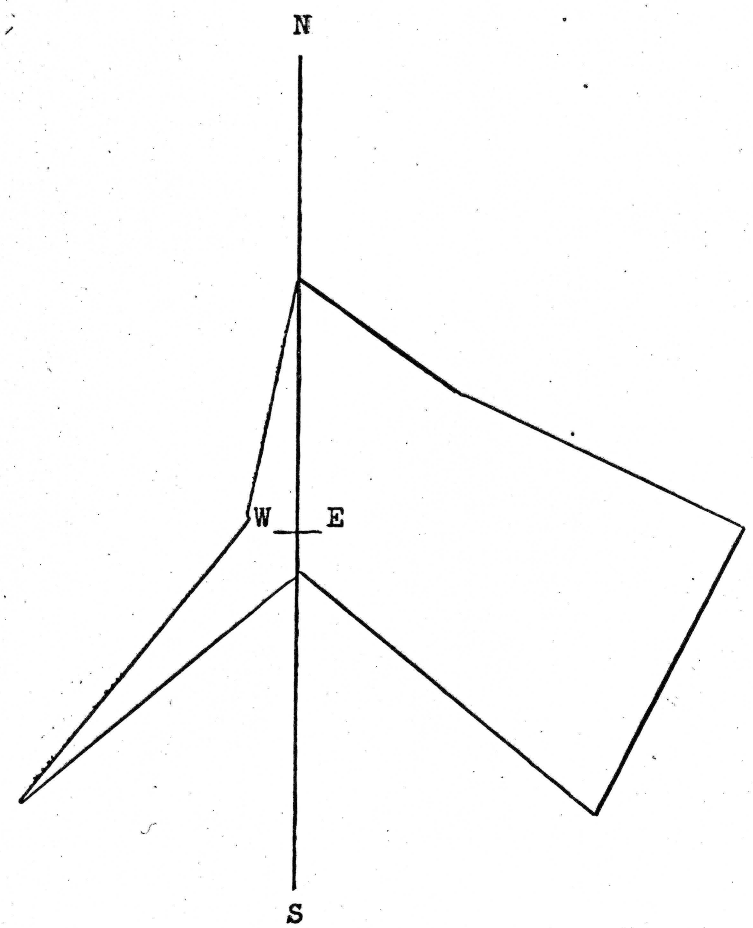
GOBABEB WINDS:

Velocity (km/hr)	5-9	10-14	15-19	Vt	20-24	25-29	30-34	35-39	40-44	45-49	50-54
Direction											
NE	70	25	13		14	14	16	5	4	6	1
E	139	43	35		40	58	49	26	20	2	1
SE	520	222	144		73	26	19	3			
S	193	224	137		7	15	4				
SW	202	267	328		231	91					
W	268	353	208		48	5					
NW	361	354	221		54	9	1				
N	563	552	308		109	32	8	4	2	2	
Total	2316	2040	1394	Vt	576	350	97	38	26	10	2

Data from NDRS (Gobabeb) for year 1966 (December) to 1967 (November). Readings taken hourly throughout year, with exception of 6½ days in February 1967.

Total calms (winds less than 5 km/hr) = 1448

Diagram 4.



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 TIMES THEIR FREQUENCY IN HOURS PER YEAR. (1" = 2000,000).

(Constructed from the data in diagram 2).

Diagram 5

SURFACE WIND SPEEDS FOR WALVIS BAY AND LUDERITZ?

(At 1500 hrs.. Source, Handbook, 1944)

WALVIS BAY

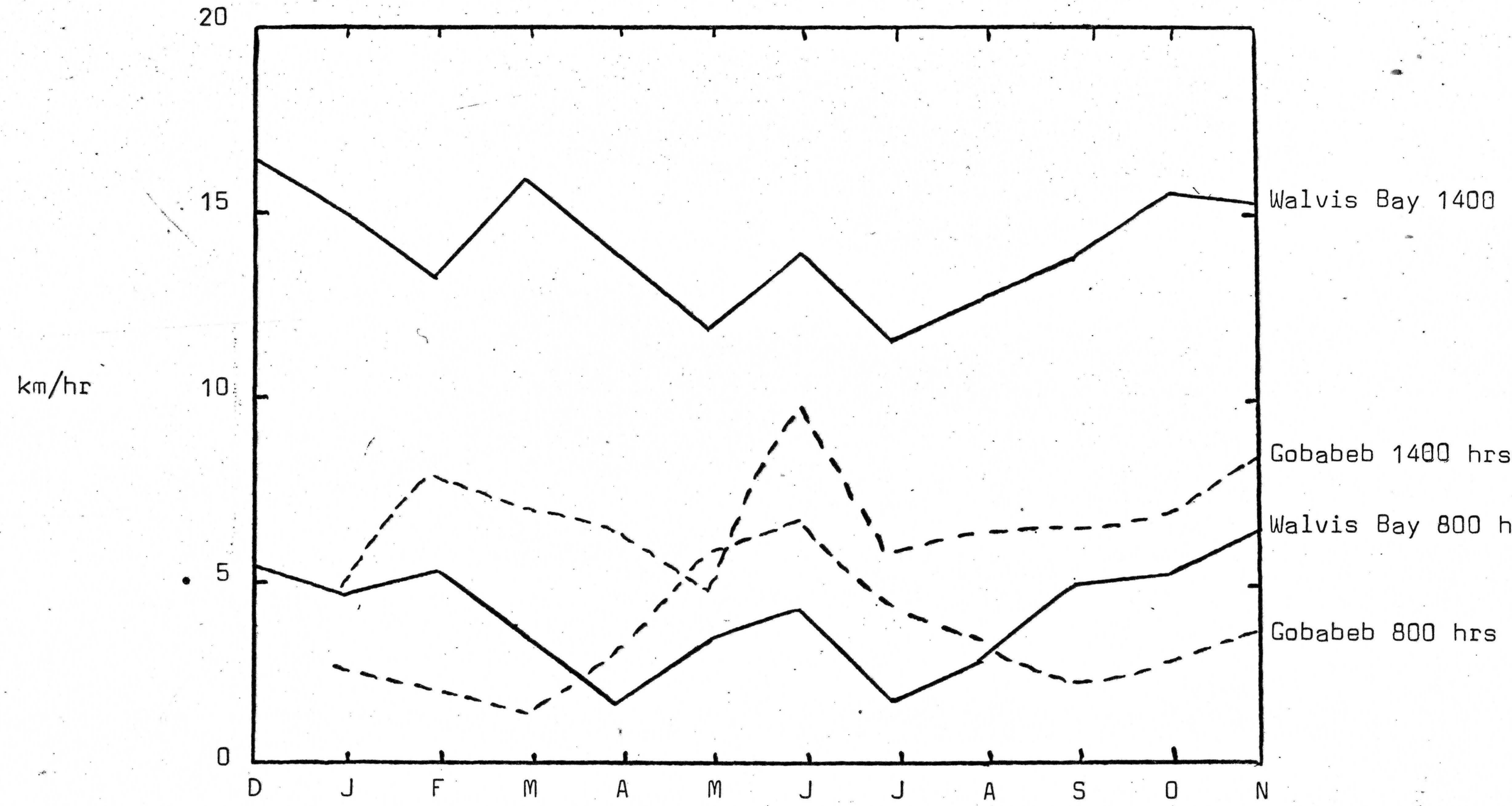
Month	km/hr	N	NE	E	SE	S	SW	W	NW	Less than 3 knots.
Dec-Feb.	3-13	1				1	34	21	8	4
	14-27					5	22	1	1	
	28-40					1	1			
Mar-May.	"					4	36	13	5	7
						9	24	1		
							1			
June-Aug.	"	3	1	1		7	33	8	9	8
						11	17			
						1	1			
Sept-Nov.	"	1				3	27	9	6	9
						12	28			
						3	2			

LUDERITZBUCHT

Month	km/hr	N	NE	E	SE	S	SW	W	NW	Less than 3 knots.
Dec-Feb.	3-13	2	1			3	5	3	11	5
	14-27					23	16			
	28-40					19	8			
	40+					2	2			
Mar-May.	"	3				11	10	3	8	10
						29	10			
						10	3			
						1	1			
June-Aug.	"	6			1	10	9	6	13	17
		1			1	17	7	1	2	
				1		6	1		1	
Sept-Nov.	"	1				2	7	6	16	5
						20	17			
						15	4			
						5	2			

Compare the frequency of events (%) of wind speed 28-40 knots.

Diagram 6



MEAN WIND VELOCITY FOR 1400 HRS AND 800 HRS
FOR GOBABEB AND WALVIS BAY
Dec. 1965 - Nov. 1966

Diagram 87

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

	Arica.[2]	Port Etienne[2]
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:

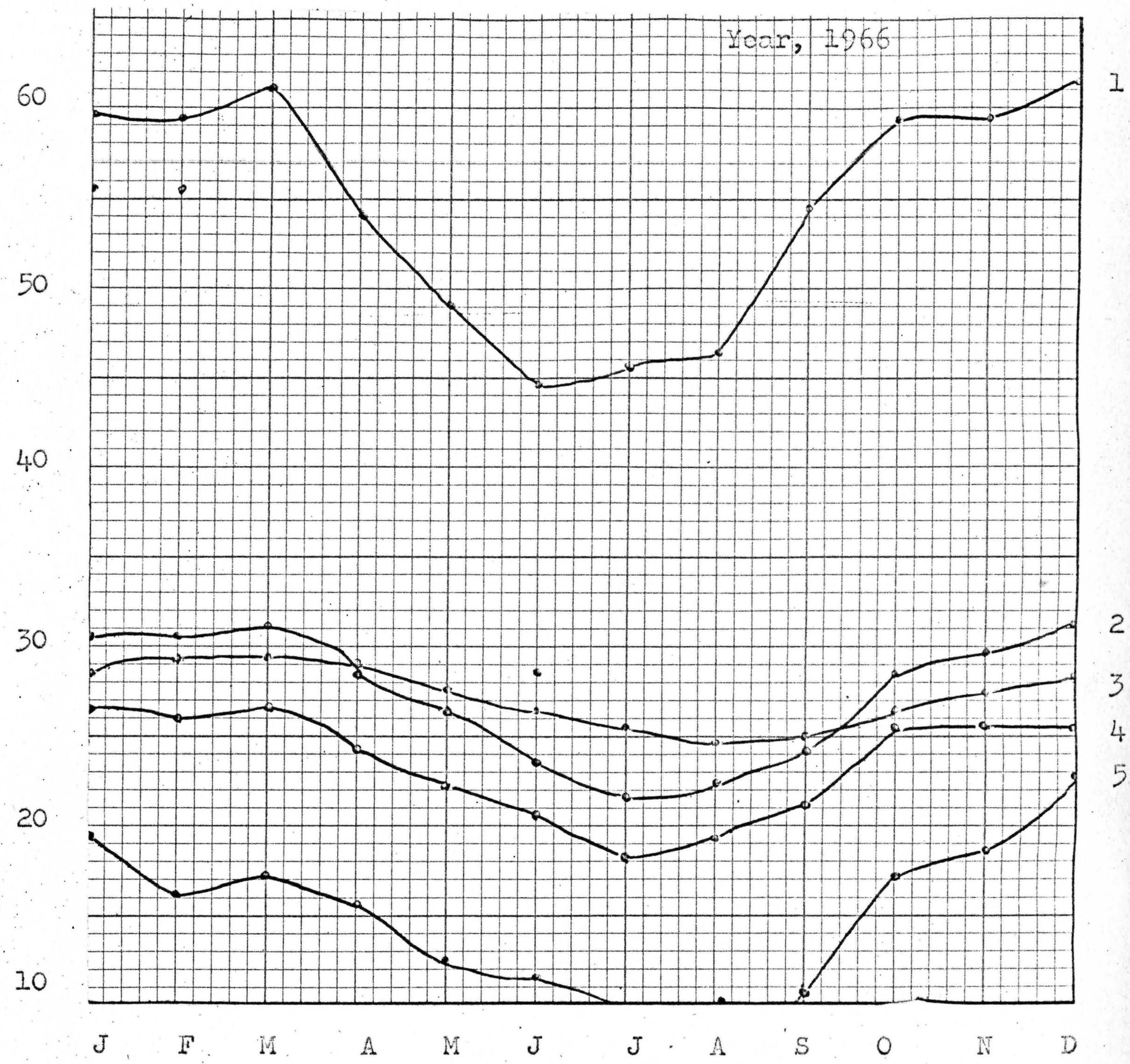
* Handbook, 1944.

\+ Records at NDRS, Gobabeb.

2. Meigs,

Diagram 8

SOIL TEMPERATURE FLUCTUATIONS AT GOBABEB



1 = Surface (1400 hrs.)
2 = 30 cms. (0800 hrs.)
3 = 120 cms. (0800 hrs.)
4 = 10 cms. (0800 hrs.)
5 = Surface (0800 hrs.)

Diagram 9

ROCK TEMPERATURE VARIATIONS AT GOBABEB

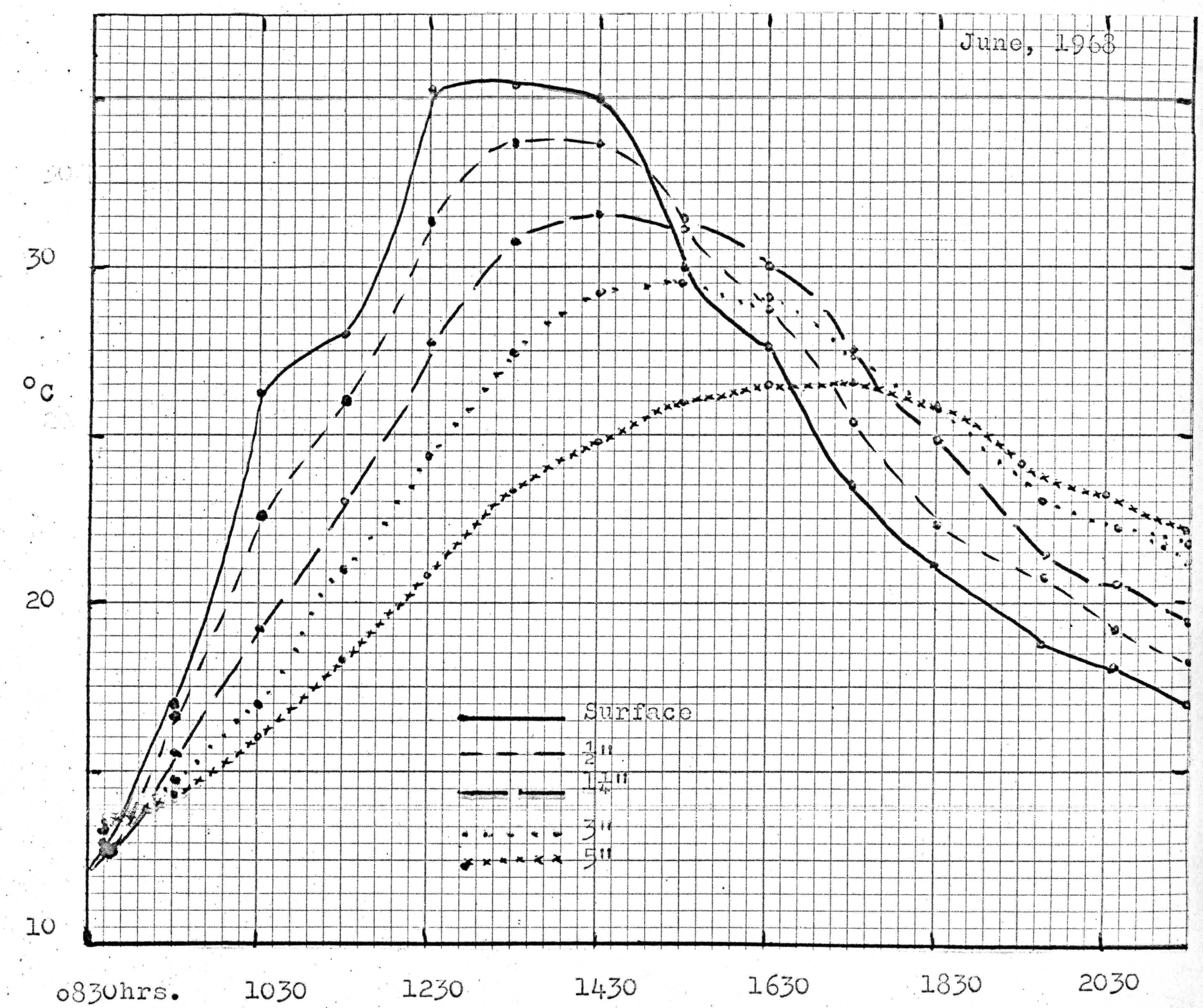
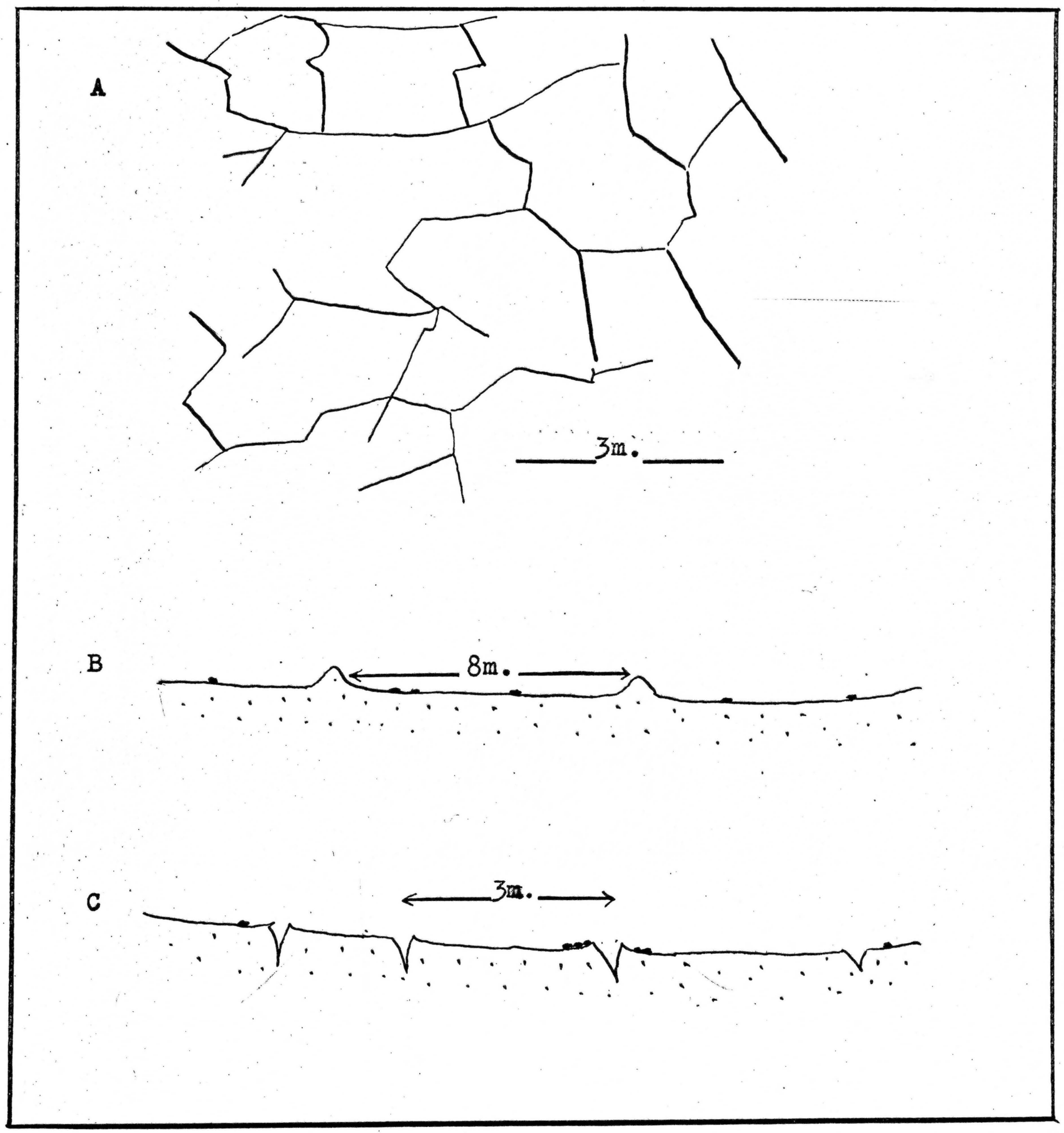


Figure 10

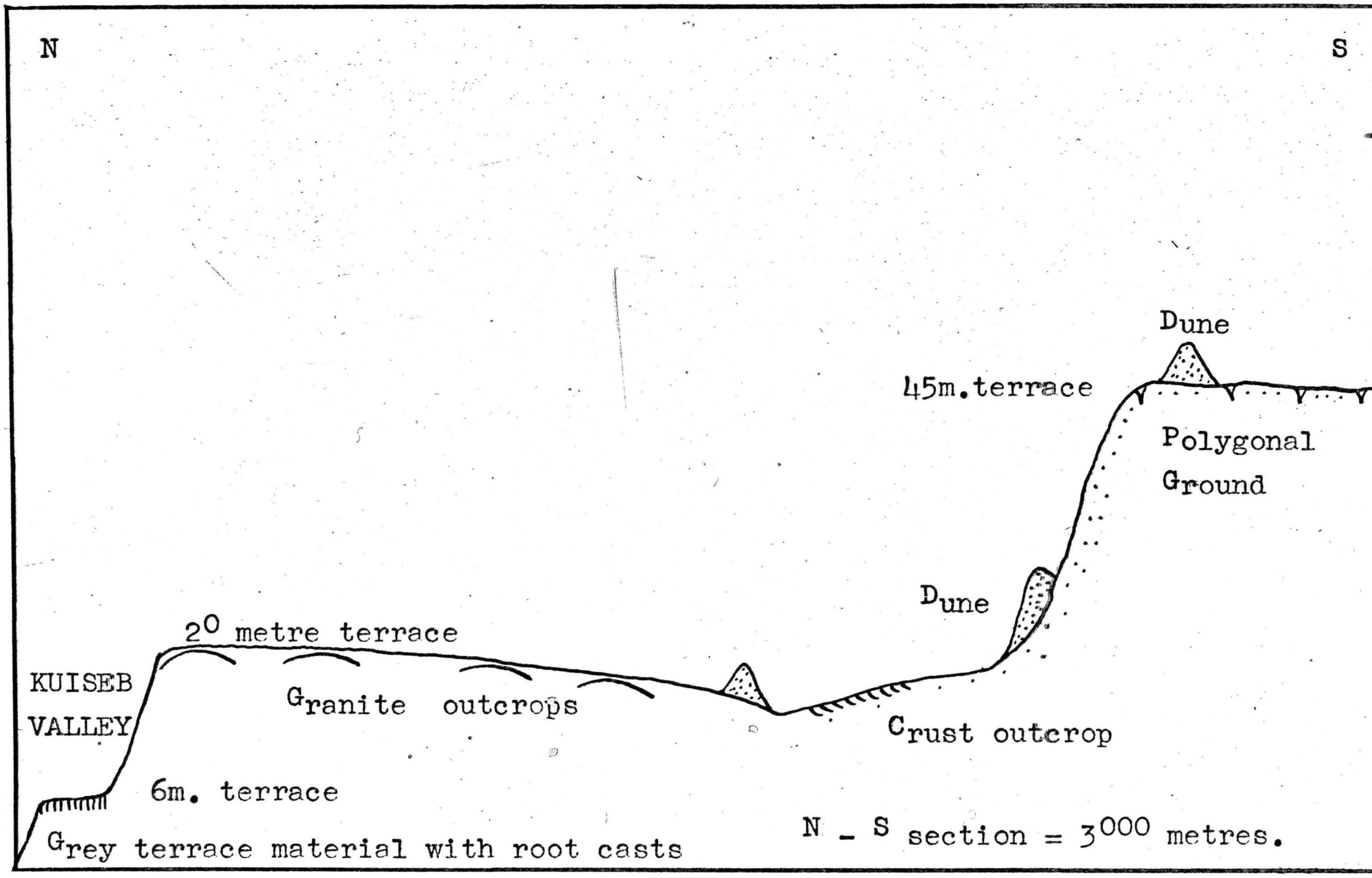
PATTERNED GROUND NEAR GOBABEB



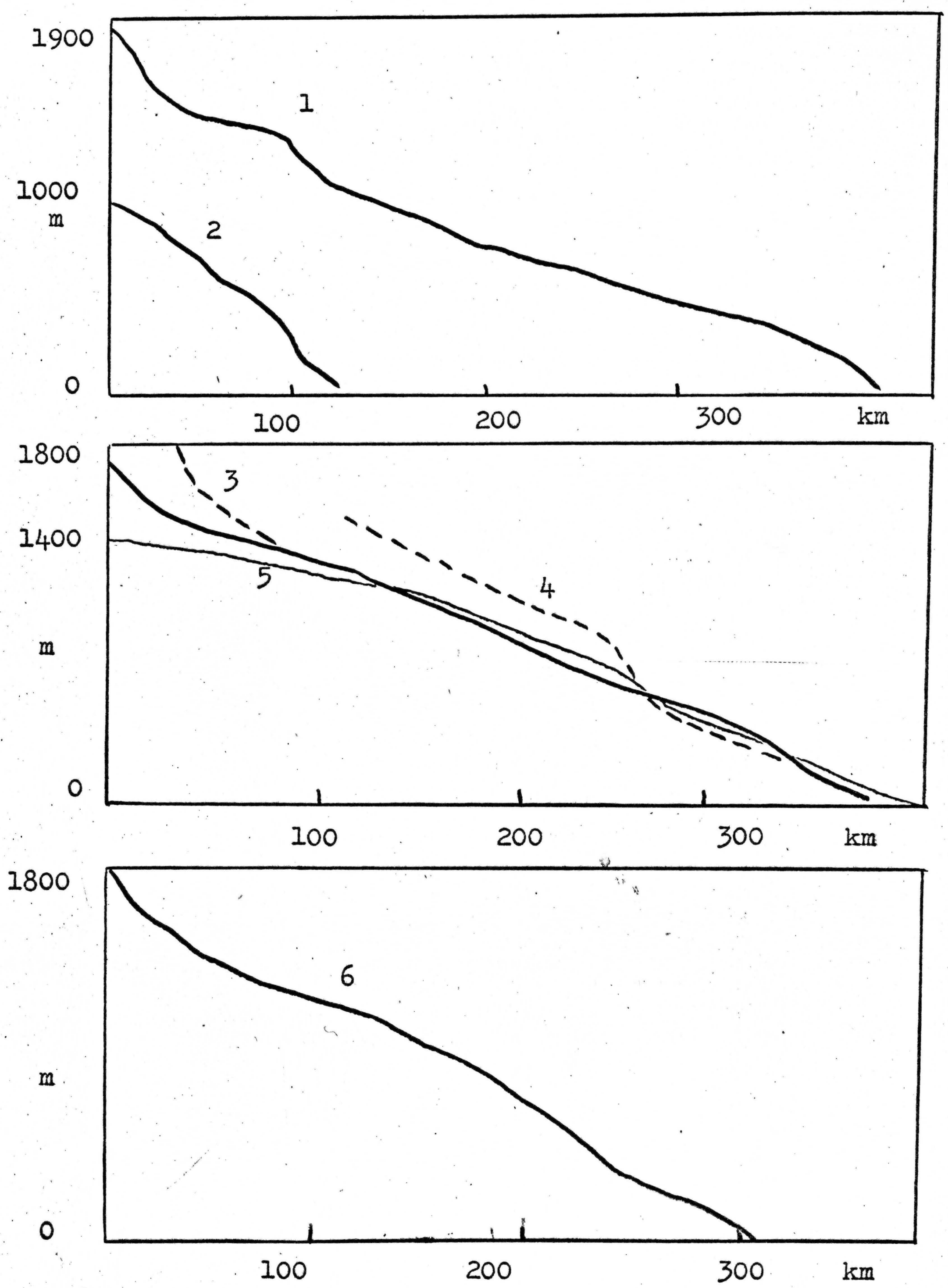
A = The horizontal pattern of part of the area of polygonal structures.

B = Cross-section of polygon with raised margins

Diagram 8


N
S
Dune
45m. terrace
Polygonal Ground
Dune
20 metre terrace
KUISEB VALLEY
Granite outcrops
Crust outcrop
6m. terrace
Grey terrace material with root casts
N - S section = 3000 metres.

12



LONGITUDINAL PROFILES OF NAMIB RIVERS
(After Stengel, 1964, 1966)

1 = Kuiseb, 2 = Tubas, 3 = Klein Windhoek running into Swakop R., 4 = Khan, 5 = Ugab, 6 = Omaruru.

Diagram 13

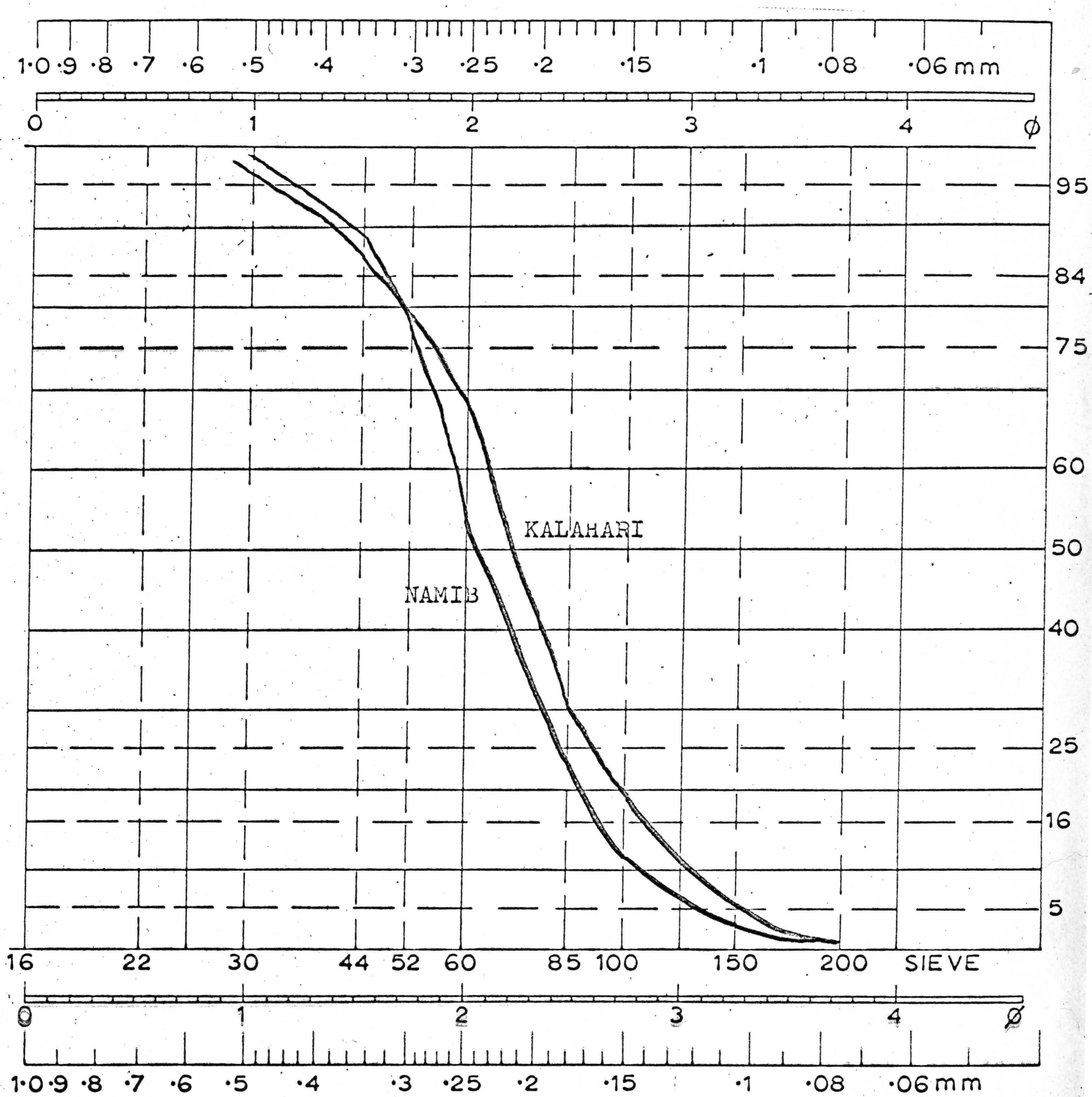
COMPARISON OF NAMIB AND KALAHARI SAND

Mean % Grain sizes			Cumulative % finer	
B.S.Sieve No.	Namib	Kalahari	Namib	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

Diagram 14



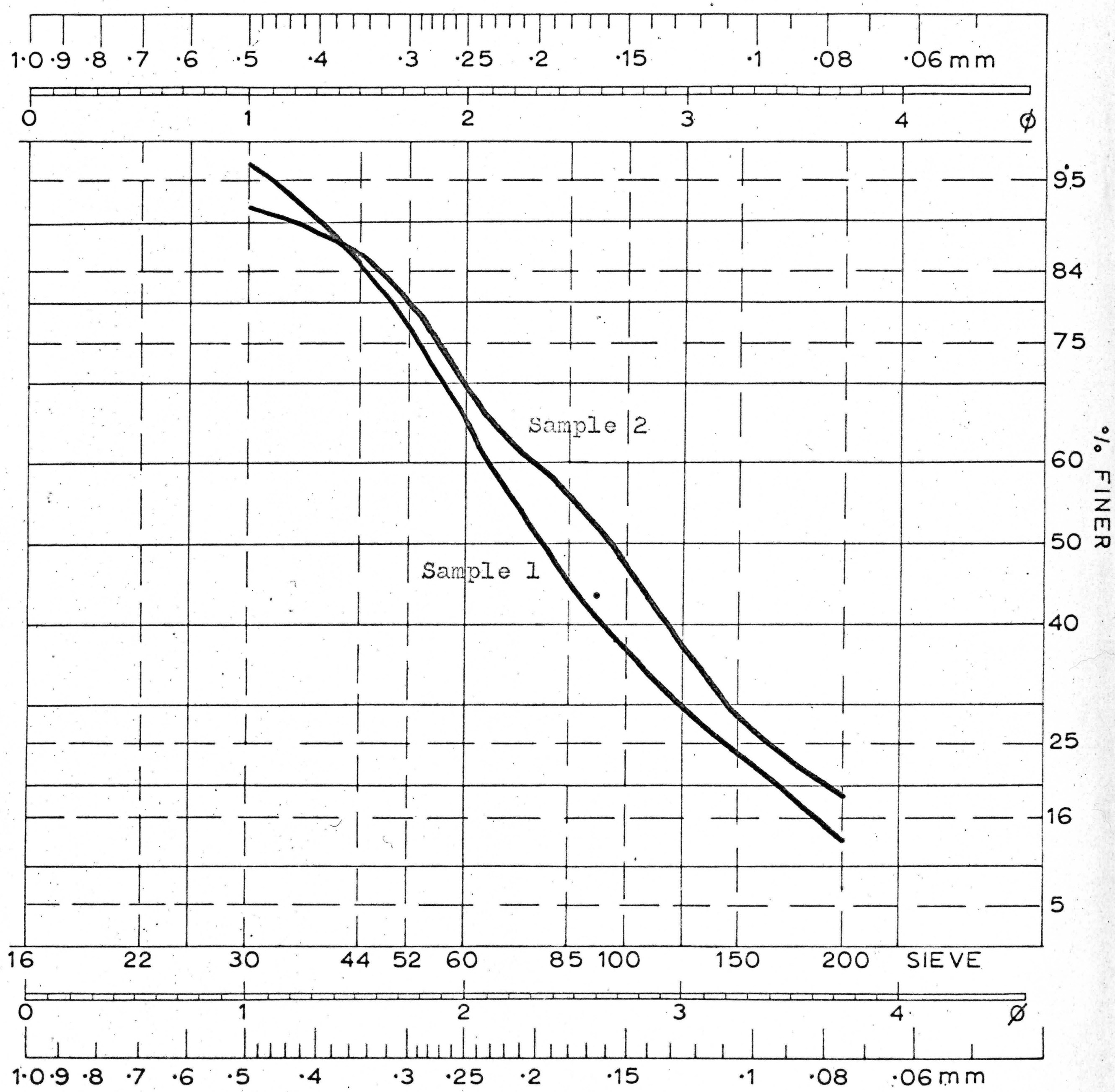
MEAN GRAIN SIZE OF KALAHARI AND NAMIB SANDS

Diagram 15

POLYGONAL GROUND PARTICLE SIZES

	1		2	
B.S. Sieve No.	%	Cum.%	%	Cum.%
30	2.45	97.50	7.11	92.83
44	10.66	86.84	6.22	86.61
60	20.63	66.21	17.71	68.90
85	20.80	45.41	11.71	57.19
100	7.61	37.80	9.85	47.34
150	12.99	24.81	18.30	29.04
200	11.26	13.55	10.00	19.04
Pan	13.55	-	19.04	-
% $CaCO_3$	3.55		43.83	

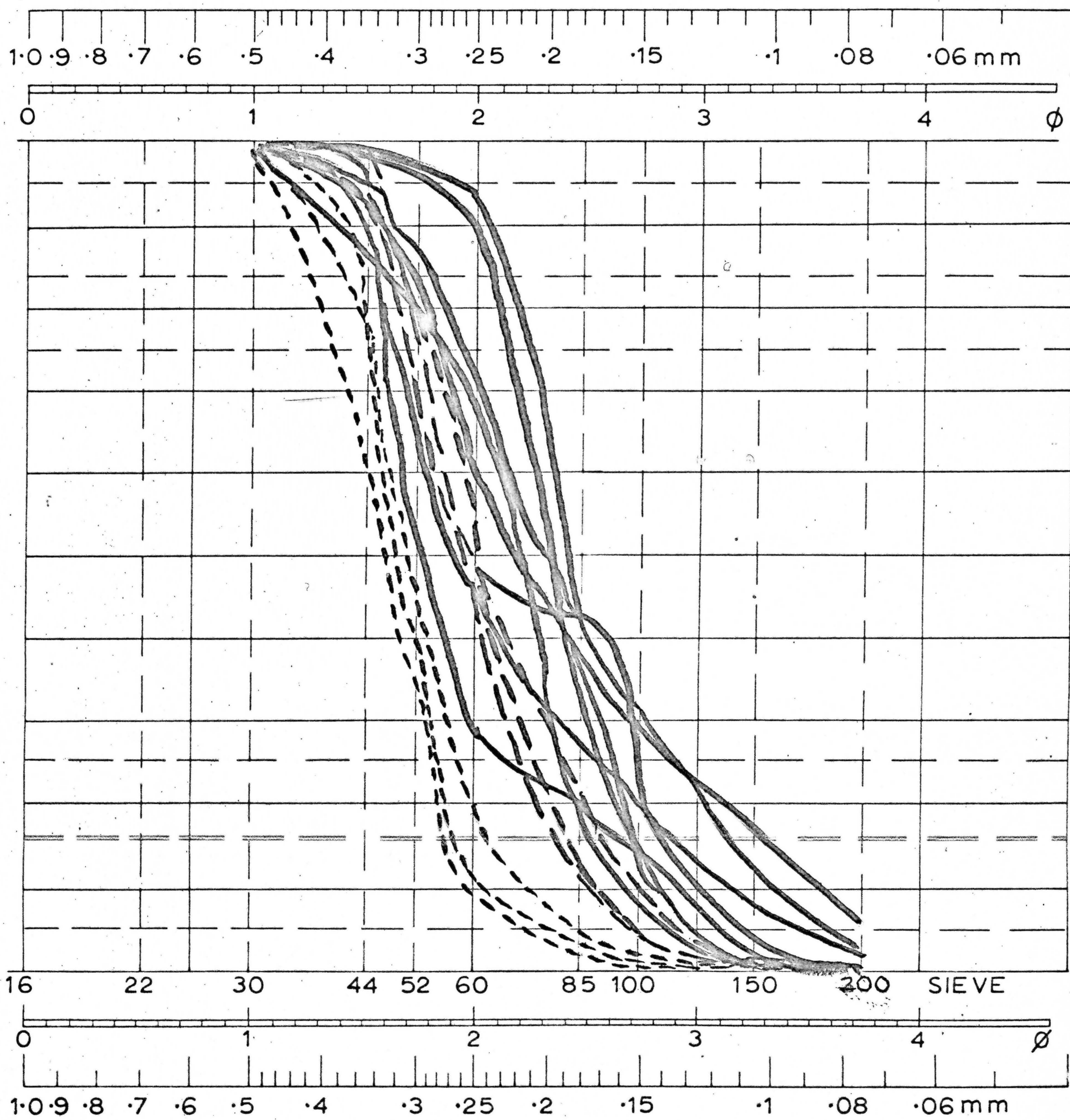
Diagram 16



PARTICLE SIZES OF POLYGONAL GROUND
MATERIAL FROM GOBABEB.

Diagram 17

GRAIN SIZE DISTRIBUTION FOR NAMIB SANDS AT GOBABEB



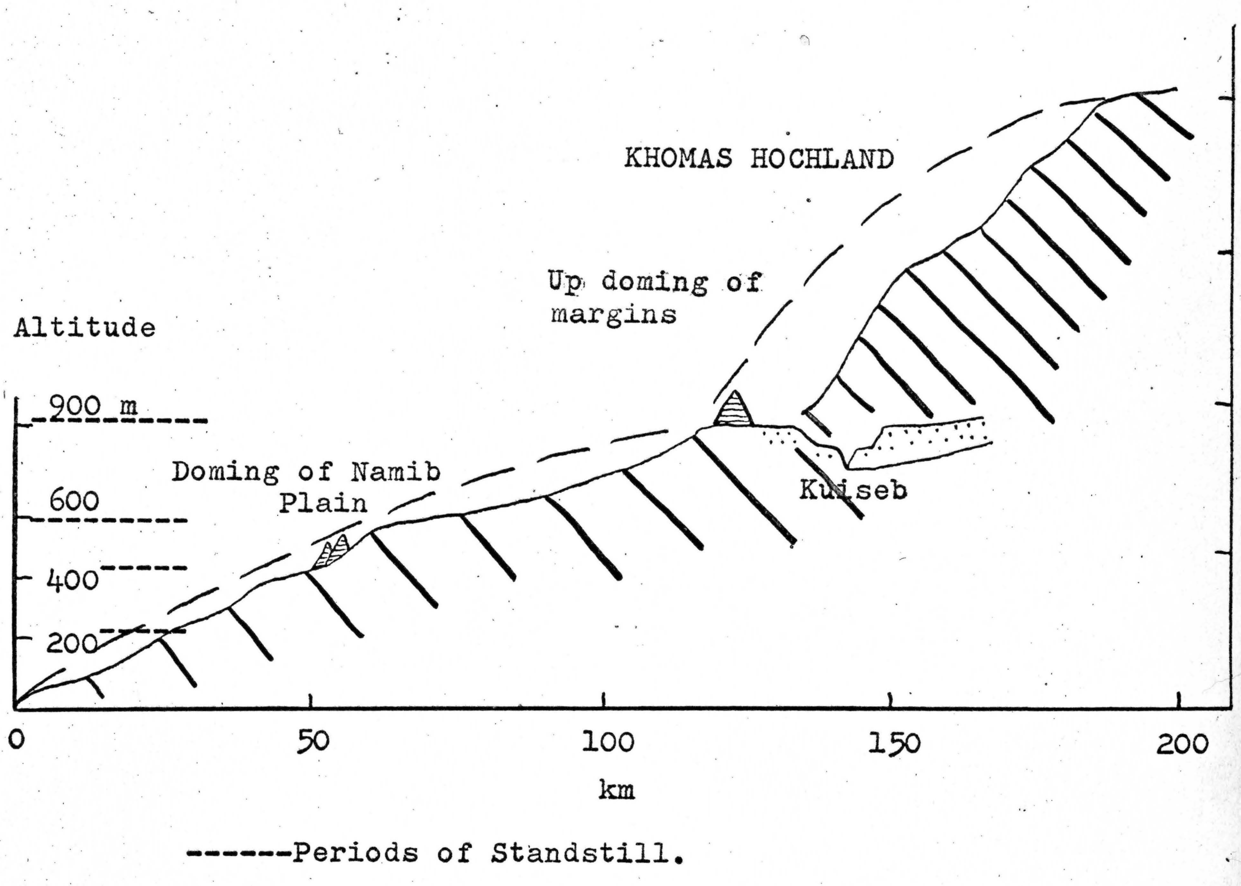
Dune crest samples   Coast samples
Other samples

Diagram 18

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

Diagram 19



SCHEMATIC REPRESENTATION OF NAMIB
SURFACES
(After Spreitzer, 1966.)

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