# History of sediments at Khommabes, central Namib Desert

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ABSTRACT

Sediments of the Khommabes depression provide evidence for a varied history of deposition and secondary alternation during the Quaternary. During a period of wetter climate, fluvial sediments, probably deposited on a former flood-plain of the Kuiseb River, were cemented by calcite to form a calcrete. The lower part of this calcrete was later altered to dolomite. Subsequently, aeolian sand, possibly derived from the flood-plain, was deposited at the basin. Renewed wetter conditions, or percolation of water from the Kuiseb River, before 27 000 B.P., resulted in additional percipitation of calcite and the growth of reeds in the basin. Aeolian dunes, deposited over this thin carbonate, were cemented by calcite 21 000 to 22 000 yrs. ago. Much of the original sediment has been deflated from the Khommabes depression, and the youngest carbonate now forms a case-hardened cap over most of the remaining sediment.

CONTENTS



## 1 INTRODUCTION

The Namib Desert includes a 34 000 km$^2$ sand sea along the western coast of southern Africa and an even larger area of exposed seaward-sloping Precambrian bedrock to the north and south. The main Namib Sand Sea extends inland for a distance of 80 to 140 km between Lüderitz and the Kuiseb River in SWA/Namibia, and is characterised by very large (50 to 150 m high) north-south trending linear dunes typically spaced 1 to 2.5 km apart (Lancaster, 1983).

Located 88 km south-east of Walvis Bay and 5 km north-west of the Namib Research Institute at Gobabeb, at 23°32′S and 14°59′E, the one-square-kilometre Khommabes depression lies at the extreme northern end of the Namib Sand Sea, one kilometre south of the Kuiseb River valley (Figs. 1 and 2). To the east and west are 60 to 100 m high linear dunes. The depression is separated from the Kuiseb River valley by an east-west transverse dune that is more than 20 m high. Along the southern side is a small area of hummocky dunes that rises less than 20 m above the roughly circular Khommabes depression (Figs. 2 and 3).

A thin (< 4 m thick) discontinuous cover of fluvial, lacustrine and aeolian sediments occurs in the depression, and these were mapped by Ward (1983) as the Khommabes Carbonate Member of the Sossus Sand Formation.

The depression is underlain by Precambrian Salem granite and Kuiseb schist, both of which are exposed in places on its floor. The elevation of the interdune corridors in the northern Namib Sand Sea is largely

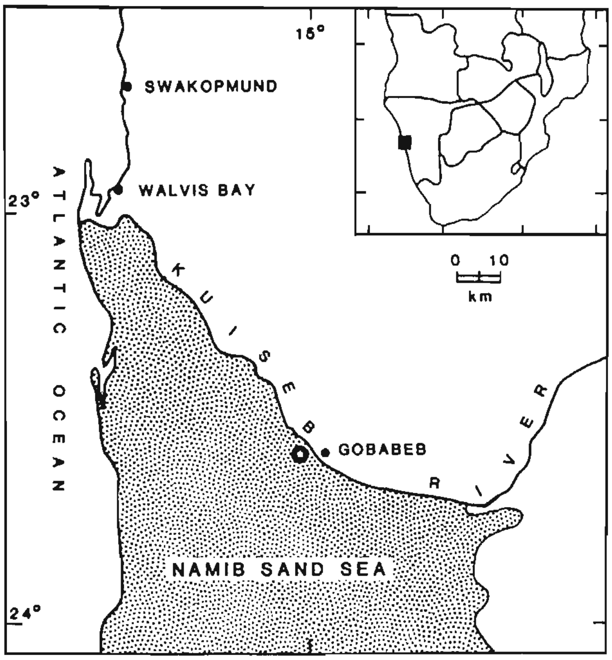


FIGURE 1: Map of the central Namib Desert showing the location of the Khommabes site just south of the Kuiseb River near Gobabeb in the northern part of the Namib Sand Sea.

controlled by this seaward-sloping, nearly-planar bedrock surface (Ward *et al.*, 1983) and by the discontinuous Tertiary Tsondab Sandstone Formation that overlies this surface in the region (Besler and Marker, 1979). The Tsondab Sandstone Formation is exposed 4 km to the south of the Khommabes depression in the same interdune corridor, where it forms an elevated area capped by the carbonate-cemented Karpfenkliff Conglomerate (Figs. 2 and 3).

The elevation of the Khommabes depression is about 380 m, similar to that of the Kuiseb River, a kilometre to the north, and it lies at the downslope end of a long interdune corridor. There are no channels leading into the basin today, and there is no record of overland flow or standing water in this corridor during the past two decades.

Our objectived is to describe the sediments at several sites in the Khommabes depression and to interpret the history of their deposition, pedogenesis and erosion. The total measured sequence contains only about 3 m of sediment but includes one of the few known buried soils in the Namib Desert, as well as several distinct sedimentary units.

## 2 HYDROLOGICAL SETTING

The climate in the central Namib Desert is extremely arid. Records at Gobabeb, 6.5 km away, indicate that the average annual rainfall over the past 18 years has been 27.2 mm, with a maximum rainfall in one day of 18.55 mm (Lancaster *et al.*, 1984). Fog precipitation, which occurs on an average of 37 days each year, adds another 30.8 mm to the annual total at Gobabeb (Lancaster *et al.*, 1984), but this does not contribute to run-off nor more than briefly to soil mositure content.

Rainfall gradually increases toward the east and, in the headwaters of the Kuiseb River, is 200 to 300 mm per year. For this reason, flow in the normally dry Kuiseb River valley depends on rainfall events more than 100 km away. At Gobabeb the mean temperature of the warmest month (March) is 24.8°C and that of the coldest month (August) 17.6°C, with daily fluctuations averaging 16.7°C (Lancaster *et al.*, 1984).

Because the Khommabes depression lies on relatively impermeable Precambrian granite and schist at the downslope end of an interdune corridor near the Kuiseb River valley, the geological setting of the basin maximises the potential for the influx and retention of water, although run-off from rainfall, at least under present climatic conditions, is very rare. During periods of substantial rainfall, the Tsondab Sandstone Formation, which outcrops only 3 km up the interdune corridor (and underlies the sand sea over a larger area to the south), as well as the adjacent dunes may store and gradually release water into the Khommabes depression; flow along the granite/schist contact in the depression may act in a similar way to provide water. Retention of water will partly depend on the configuration of the downslope end of the bedrock floor

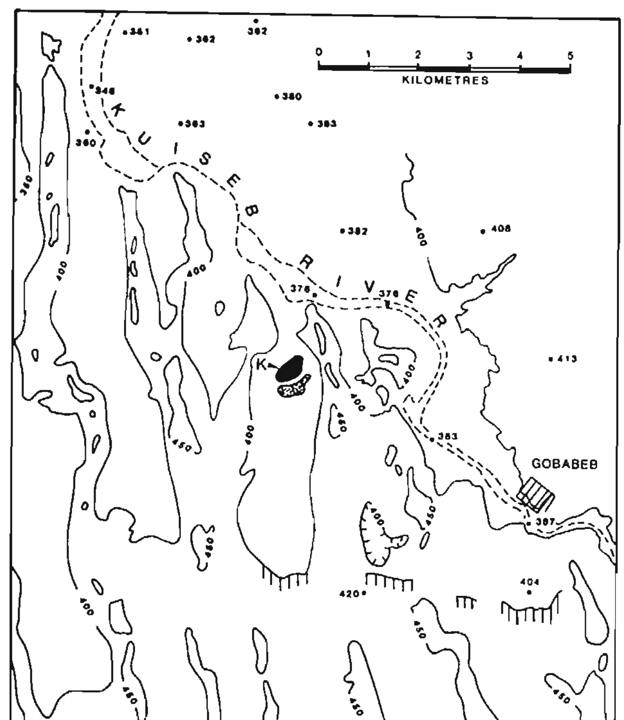


FIGURE 2: Topographic map showing location of Khommabes depresssion (K) between linear dunes at northern edge of Namib Sand Sea. Contour interval 50 m; spot elevations in metres (from 1:50 000 topographic maps 2314 BD, 2314 DB, and 2315 CA). Low, hummocky dunes with nara to south of depression are stippled. Northern edge of exposed Tsondab Sandstone FM shown by vertical lines.

and/or on the nature (permeability) of the dune barrier there. Ground-water flow through the basin sediments could occur during wet periods without any barriers to impound surface water.

The Kuiseb-River may also have supplied water to the Khommabes basin, either by seepage through the dune that now separates the river from the basin or by surface flow up into the interdune corridor prior to accumulation of the dune barrier. Flow today occurs at times up into valleys that are tributary to the Kuiseb when flood levels are high. Pleistocene hydraulic ponding of sediment in tributaries upstream from Gobabeb has been largely possible for deposition of the 30 m thick Homeb silts during this type of flooding (Ollier, 1977; Ward, 1983). Furthermore, the modern dune configuration around the Khommabes depression may not have existed during part of its depositional history, and the present basin, which lies at an elevation similar to that of the Kuiseb River valley prior to the invasion of linear dunes of the Namib Sand Sea. In fact Marker (1977) and Wienecke and Rust (1973) have suggested that the Kuiseb River, downstream from about Gobabeb, may have been displaced northwards by the advancing dunes to its present location.
cation.

## 3 KHOMMABES SEDIMENTS

### 3.1 General nature and distribution

Sediments in the Khommabes basin cover only part of the roughly 1 km-diameter depression between the dunes. Post-depositional erosion has been substantial and a large low "island" of fresh Salem granite outcrops occurs near the centre of the basin (Figs. 2 and 3) as well as in scattered places along its southern margin. A xenolith of Kuiseb schist is exposed on the floor at the northern edge. Deflation is continuing to remove sediment from the basin today, as well as from some of the adjacent dunes.

In general, the centre of the depression is flat, with up to 2 m of relief, and bedrock and calcrete are exposed (Fig. 3). The sediment cover is thickest south of the central bedrock "island", with more than 2 m exposed along the wind-eroded higher elevations of the margin. Because of deflation of former dune margins to the south, east and west, and because of aeolian deposition of the north, the original extent of the Khommabes deposits is not known.

Our field efforts were concentrated in the southern part of the basin, south of the bedrock "island". Figure 4 is a schematic cross-section across this part of the basin, showing the location of the three stratigraphic sections described in this paper.

### 3.2 Description of sediments

Tables 1 to 3 describe sediments at three sites in the southern Khommabes depression. Descriptions are based on field examination and laboratory studies,

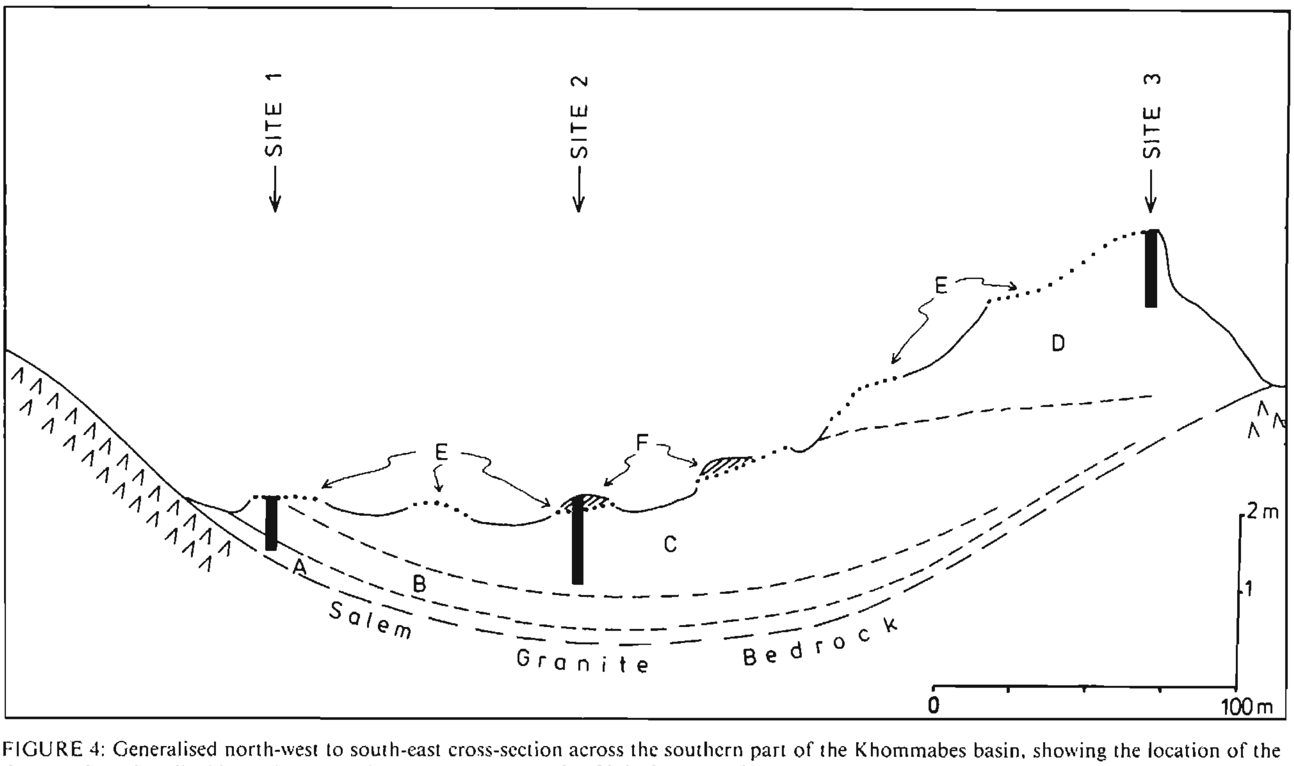


FIGURE 4: Generalised north-west to south-east cross-section across the southern part of the Khommabes basin, showing the location of the three sections described in Tables 1, 2 and 3. Letters correspond to Units in these tables and in the text. Dashed lines show possible stratigraphic relationships, with heavy bars representing measured sections. Vertical exaggeration 25X.

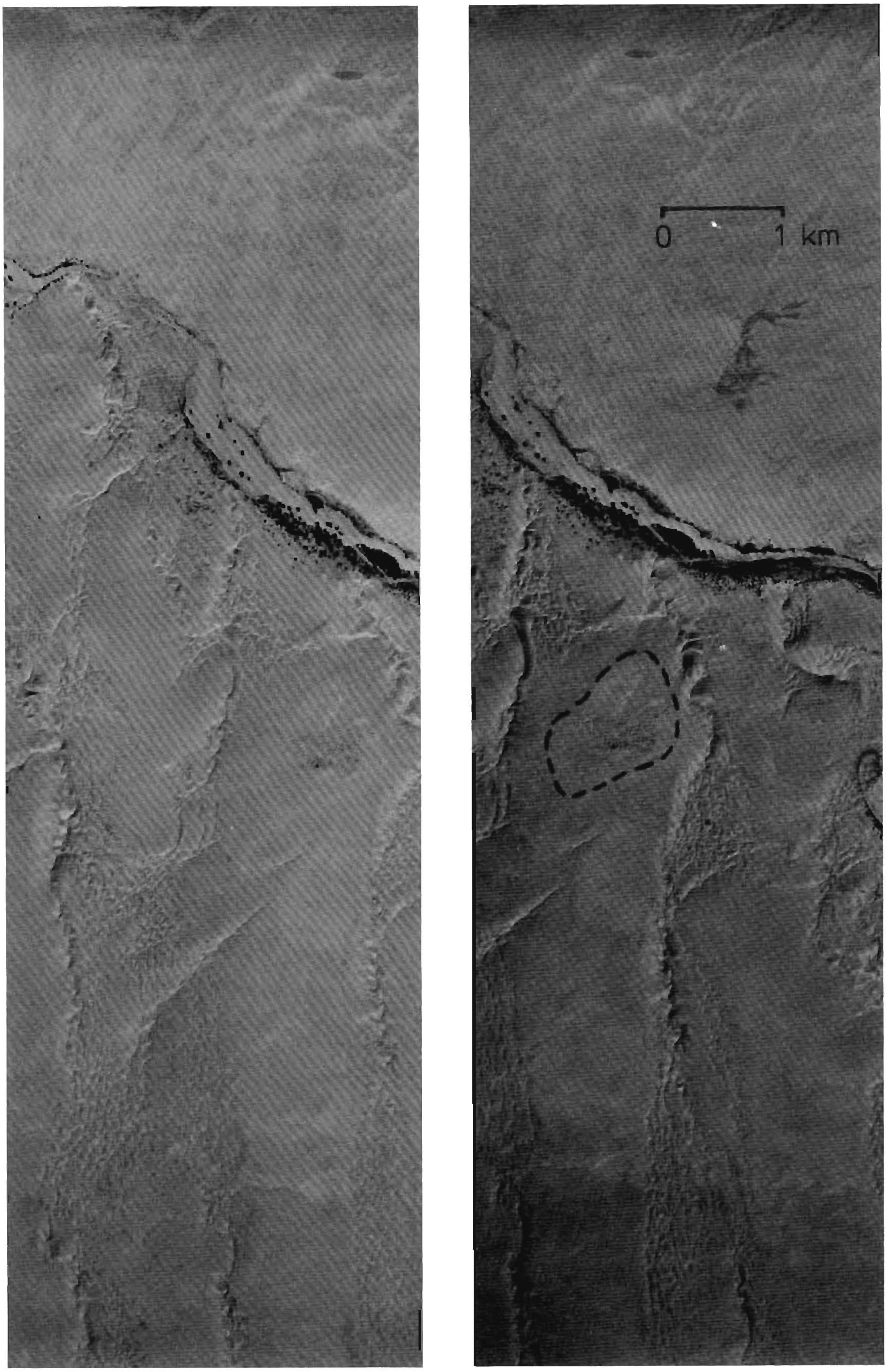


FIGURE 3: Stereophoto showing the Khommabes depression (dashed outline) and bordering dunes. The Kuiseb River valley and its scattered vegetation (dark tones) separates the Namib Sand Sea from the bare bedrock to the north. The hummocky dunes on the southern side of the Khommabes basin are also sparsely vegetated. The lightest tones in the basin, south of the somewhat elliptical "island" of Salem granite, are exposures of calcrete cemented sediment. The Tsondab Sandstone Formation is exposed at the highest interdune elevations south of the Khommabes basin. Photographs reproduced under Government Printer's Copyright Authority 8104 of 8-5-1984.

TABLE 1: Description of sediments at Site 1 (Fig. 4) in the Khommabes basin.

| Unit | Thickness in cm | Description |
|---|---|---|
| E | 0—5 | Sandy dolomitic limestone crust, 66% calcite and dolomite, sand is dominantly very fine grained quartz having same properties as underlying unit, crust is hard and brittle, vesicular and honeycombed, light grey (10 YR 7/2). |
| B | 53 | Sandstone, cemented by dolomite or ankerite (27% near base to 67% near top), and some halite in upper part, sand is fine to very fine grained quartz and albite with occasional very coarse sand to granules of white vein quartz in the basal 20 cm (decreasing upward), quartz mainly (> 60%) angular and clear with some sub-angular to rounded clear and amber grains, < 5% of quartz is stained red (2.5 YR 4/8), frosted grains common in upper part, < 5% mica, < 2% dark minerals, no apparent laminae, brown tubules in upper part, overall white (10 YR 8/2), upper contact distinct. |
| A | 10 + | Sandy dolomitic limestone, granite grus with 75% calcite and dolomite cement, grains mainly (> 80%) angular clear quartz and granite rock fragments, occasional sub-rounded amber quartz grains, < 5% mica and dark mineral grains, friable to hard, white (10 YR 8/2), upper contact distinct. |

including, chemical, sieve, microscope and X-ray diffraction analyses.

Although the total measured stratigraphic sequence is less than 3 m, a number of major events are recorded. We have divided the sequence into units based mainly on field observations, and have correlated these using both field and laboratory criteria (Fig. 4). A major problem in correlation is the presence of secondary minerals in the clastic sequence, which have altered and obscured some of the primary sedimentary features.

Basically, the sequence is composed of fine quartz and albite sand and silt cemented by variable amounts of calcite and dolomite and relatively small percentages of other secondary minerals. In places, the calcite and dolomite cement makes up more than 50% of the unit and the sediment may be appropriately called a sandy limestone or dolostone. Except in the mantle of weathered granite (Unit A), all quartz is stained an amber to "blotchy" red colour and shows some rounding. Both rounding and extent of staining, however, are not as great as in the modern dunes of the Namib Sand Sea, except in the uppermost sandstone (Unit F). There does not seem to be a close correlation of

TABLE 2: Description of sediments at Site 2 (Fig. 4) in the Khommabes basin.

| Unit | Thickness in cm | Description |
|---|---|---|
| F | 20 | Sandstone, fine to coarse grained, cross laminated with dips 12° NNE, individual laminae weakly and variably cemented by calcite ($\bar{X}$ = 22%), sand is mainly sub-round to rounded amber to yellowish red (5 YR 7/6) quartz, < 2% clear, < 5% angular or sub-angular, no mica, < 3% dark minerals and rock fragments, overall light reddish brown (5 YR 6/4). |
| E | 0.2—2.0 | Sandstone, fine to very fine grained, cemented by 38% calcite (moderately hard but friable), mainly sub-angular to rounded clear (30%) and amber* to red**-stained quartz, trace of mica, < 5% dark minerals (mainly rounded), pinkish grey (7.5 YR 7/3), pitted distinct upper surface and irregular distinct base. |
| C | 10—15 | Silty fine to very fine sand, poorly sorted, poorly laminated parallel to irregular base, very weakly cemented by calcite along some laminae, mainly sub-angular to rounded amber to red-stained quartz, < 3% mica, <5% dark minerals (mainly rounded), brown (7.5 YR 5/4), upper contact irregular and distinct. |
| C | 10—15 | Silty fine to very fine sand, poorly sorted, poorly laminated parallel to irregular base, very weakly cemented by 3% calcite, overall a distinct dark reddish brown colour (5 YR 3/3), occasionally mottled with lighter brown colours, mainly sub-angular to rounded quartz with a medium to dark amber stain on all grains, albite abundant, 5—10% mica, 5—10% dark minerals (most well rounded), modern rootlets abundant, upper contact colour distinct and irregular, lower contact gradational over 1 cm. |
| C | 5—8 | Silty fine to very fine sand, poorly sorted, well laminated, very weakly cemented by 3% calcite with some concentration as nodules along laminae, mainly sub-angular to rounded amber to red-stained quartz, < 5% clear quartz, albite abundant, 5% mica, < 5% dark minerals, light brown (7.5 YR 6/4), upper contact gradational with up to 10 cm relief. |
| C | 20 | Coarse siltstone to fine grained sandstone, poorly sorted, well laminated, moderately well cemented (but friable) in lower part, but poorly cemented by calcite with platy structure near top, variably cemented along laminae, mainly sub-angular to rounded clear (20%) to amber (70%) quartz with some red staining, albite abundant, 5% mica, < 2% dark minerals, pinkish white (7.5 YR 8/1), upper contact gradational over 1 cm. |
| C | 20 + | Limestone with 40% coarse silt to fine quartz sand, poorly bedded, no apparent laminae, hard, sand angular to rounded (mainly sub-angular to sub-rounded) albite and quartz that is clear (40%) and amber to red-stained, 3% mica, < 5% dark minerals, some dolomite and halite cement, scattered poorly cemented reddish tubules of sand, overall white (10 YR 8/2), upper contact based on absence of laminae and hardness. |

* *Amber quartz grains comprise a variety of lightly-stained transparent grains with colours commonly close to 7.5 YR 7/6 (reddish yellow).*

** *Red quartz grains commonly have a "blotchy" opaque coloration concentrated in pits and embayments; they may be as dark as red (2.5 YR 4/8 and 10 R 4/8) but normally become a transparent pale red to amber colour outside of the embayments.*

rounding and coloration, although highly angular grains are rarely stained. The darker red staining, which can be as dark as 2.5 YR 4/8 and 10 R 4/8 and is opaque, is concentrated in pits and embayments on many quartz grains; commonly this becomes a transparent pale red to amber colour outside of these sites of concentration.

TABLE 3: Description of sediments at Site 3 (Fig. 4) in the Khommabes basin.

| Unit | Thickness in cm | Description |
|---|---|---|
| E | 5—20 | Sandy limestone crust, 67% calcite, sand same as underlying unit, crust is hard and brittle and contains scattered tubiforms structures and calcified *Phragmites* stems, honeycombed and irregular, light grey (10 YR 7/2). |
| D | 100+ | Sand, very fine to fine sand in upper part becoming medium to very fine sand in lower half, well sorted, no visible laminae, mainly subangular to subrounded amber quartz sand, < 5& red-stained grains, < 2% mica, < 5% dark minerals (most rounded), non-calcareous, upper 55 cm variably stained and mottled strong brown (7.5 YR 5/8), brown (7.5 YR 4/6), yellow red (5 YR 5/8), and dark yellowish brown (10 YR 3/4) with a little iron oxide cement, becoming light yellowish brown (2.5 Y 6/4) in lower part, upper contact distinct but irregular. |

Bedding is well-developed in the sequence, but finer laminae and sedimentary structures are poorly exhibited in the well-cemented units (Units A, B, E). Only the uppermost sandstone (Unit F) exhibits cross bedding. Nearly horizontal laminae are common in Unit C, and Unit D is massive.

In summary, the sequence contains, from bottom to top: 1) calcrete-cemented granite grus (Unit A); 2) dolocrete-cemented fine sand (Unit B); 3 silty very fine sand with a soil and calcrete developed in it (Unit C); 4 fine sand (Unit D); 5) a thin calcite-cemented sand with calcified *Phragmites* stems and root casts (Unit E); and 6) calcified aeolian sand (Unit F). The "Unit" designations are based on *primary* sedimentary components. Superimposed on these units are several events of pedogenic activity, which have modified the original sediment and have influenced the erosional history in the Khommabes basin.

PLATE 1: View of Khommabes depression from transverse dune at north end. Sediments investigated lie in middle distance as indicated by arrow.

## 4 HISTORY OF KHOMMABES SEDIMENTS

### 4.1 Introduction

The Khommabes depression (Plate 1) is located at the northern edge of the present Namib Sand Sea between large linear dunes, only a kilometre south of the Kuiseb River. Although hyper-arid conditions and widespread aeolian sands have probably existed in the Namib since the Pliocene (Ward *et al.,* 1983), the northern boundary of the sand sea may not have been established in its present position until much later. Ward (1982) provides stratigraphic evidence for the presence of large linear dunes in the Oswater Conglomerate on the south bank of the Kuiseb River upstream from Gobabeb. These may have accumulated in the Middle Pleistocene (Korn and Martin, 1957; Ward *et al.,* 1983). Although the Kuiseb probably was established along its present course up-stream of Gobabeb by the early Pleistocene, down-stream from this point the river is not confined in a deep bedrock valley and it is likely that the river has been progressively displaced to the north by the advance of the sand sea. This has occurred as a result of the down-stream decrease in discharge of the Kuiseb by evaporation and percolation into the alluvial fill, combined with a more rapid northward migration of dunes in the western region (Ward, 1983). Up-stream, the deep, narrow valley and higher discharge and erosive power of the Kuiseb River have combined to keep pace with the influx of aeolian sediment from the sand sea.

Most of the discharge of the Kuiseb River is derived from run-off in the bedrock escarpment zone and the Khomas Hochland to the east (Stengel, 1964; Marker, 1977). This means that precipitation events well outside the Khommabes area have probably had considerable influence over sediment deposition and secondary alteration of that sediment. As a result of its control on the northern margin of the Namib Sand Sea and of its influence on river and ground-water base flows, the Kuiseb River probably has been the major sedimento-logical factor in the Khommabes area throughout the Quaternary. Only during the wettest periods, when precipitation was great enough in the

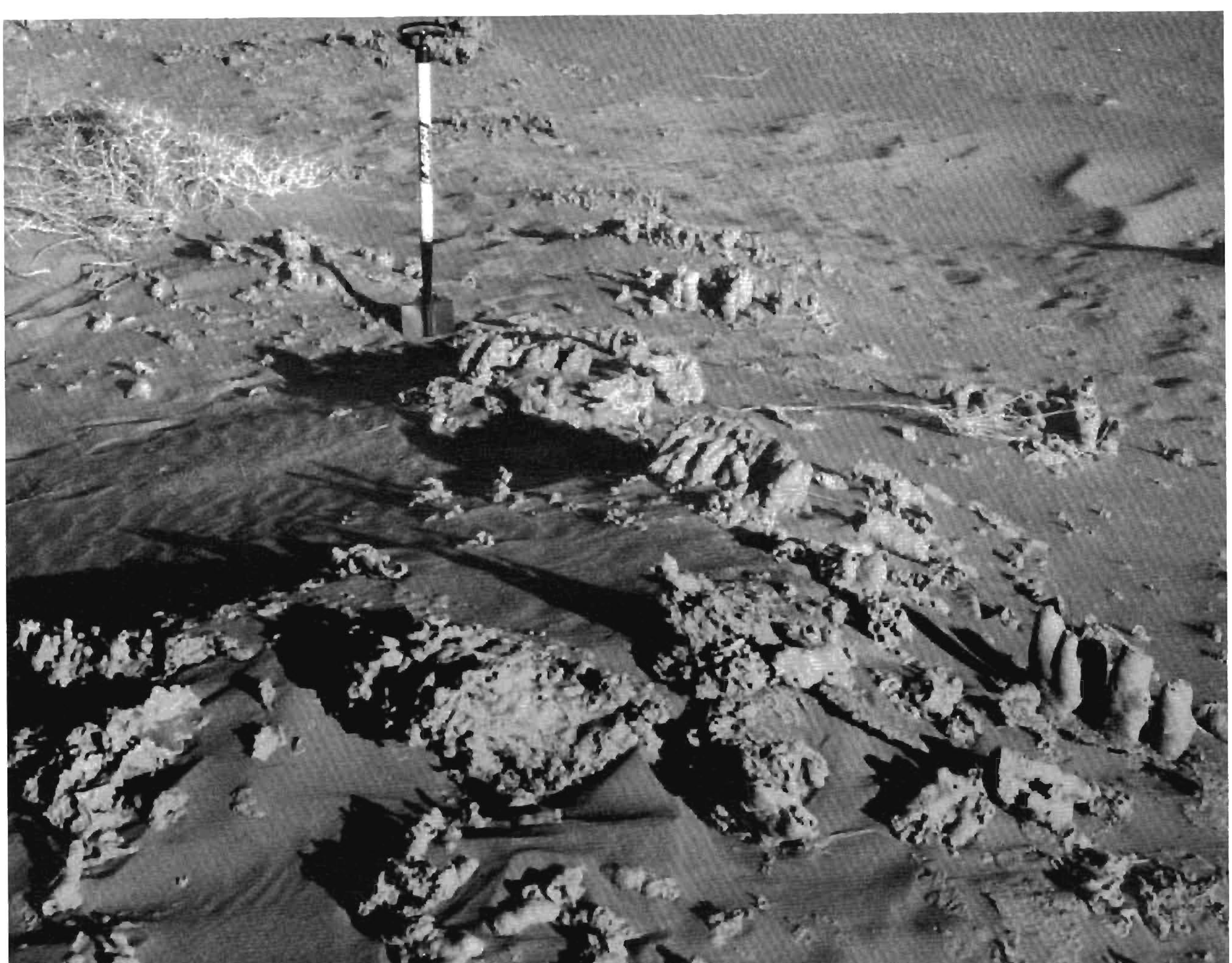

PLATE 2: Calcareous-cemented root or termite tubes in sand of Unit F.

local area to cause surface run-off in the interdune corridors of the Namib Sand Sea or to recharge the Tertiary Tsondab Sandstone Formation aquifer, would events in the Khommabes depression not have been controlled primarily by flow in the Kuiseb River valley.

## 4.2 Bedrock weathering

The upper part of the buried granite surface in the Khommabes basin has been disaggregated by the growth of calcite. Dolomite is also common and represents a later phase of cementation or alteration of calcite. The granite grus that developed is now cemented by calcrete (Unit A, Table 1), and a hard sandy dolomitic limestone shell, comprised of up to 75% carbonate, has developed. Scholz (1972), Goudie (1972) and Martin (1963) have described examples of bedrock decomposition in the region by both calcite and gypsum. Carbonate probably originated from Precambrian rocks as well as from the extensive Tertiary calcretes of the region. Ground-water emanating as springs (Sweeting and Lancaster, 1982) as well as dust and aerosols (Goudie, 1972; Annegarn *et al.*, 1978) also contain considerable quantities of calcium, calcium carbonates and magnesium.

A small percentage of slightly rounded and stained detrital grains is included in our samples of Unit A. This indicates that some local reworking of the granite grus took place before calcretisation.

## 4.3 Alluvial sedimentation

Unit B is a fine to very fine quartz sand that contains coarse sand to granules in the basal part. Although it has a high percentage of fresh angular unstained quartz similar to that in the underlying grus, about 40% of the quartz is somewhat rounded and many grains are stained an amber colour. All primary sedimentary structures are obscured by the dolomite, or possibly ankerite ($Ca(Mg, Fe, Mn)(CO_3)_2$) which cements this unit; weaklycemented and dark-stained tubules, probably formed by roots, are present in the upper part of the unit. The degree of sorting, colour, grain angularity, and presence of considerable mica suggest a fluvial origin. The dolomite, which ranges from 27% near the base of the unit to 67% near its top, was probably originally precipitated during weathering as calcite (calcrete), and was altered to dolomite (dolocrete) at a later time. Frosted quartz in the upper part of Unit B is attributed to pitting by calcite replacement during calcrete formation.

Unit C is a poorly sorted silty quartz sand that is exposed over much of the southern part of the Khommabes depression at elevations slightly above Units A and B; at no place was the contact with the older units observed. In places (such as at Site 2, Fig. 4), this unit is buried beneath younger sediment. Laminae are distinct except in the lower part which is cemented by 60% calcite to form a massive calcrete. Unit C has a lower percentage of clear angular grains than does the underlying alluvial unit, and this percentage decreases upward. Most grains are stained an amber colour. Mica is abundant and most black mafic minerals are well-rounded. The lower part of this unit contains poorly cemented tubules similar to those in Unit B.

We interpret Unit C as fluvial sediment, probably deposited on a flood-plain. Because Unit Cas fluvial sediment, probably deposited on a flood-plain. Because Unit C is similar in many ways to Unit B, it seems likely that they were formed in a similar sedimentary environment, perhaps during the same period of time. The proximity to the modern Kuiseb River valley and an overall similarity to alluvial sediment in that valley suggests deposition by the Kuiseb River prior to the time when aeolian dunes formed the modern barrier between Khommabes and the river. The scarcity of rounded and redstained quartz that is so common in the dunes of today's Namib Sand Sea may mean that these dunes had not yet reached the Khommabes area by this time. Alternatively, deposition could have been between linear dunes by waters of the Kuiseb River that flooded up the interdune corridor as far as Khommabes before the transverse dune that separates the site from the present river (Figs. 2 and 3) was built. We believe that in the latter situation at least some clayey sediment would have been deposited because of the low energy conditions in the "cul-de-sac" , but none has been found.

Weathering of Unit C has produced a distinctive thin dark reddish brown horizon in the upper part of the

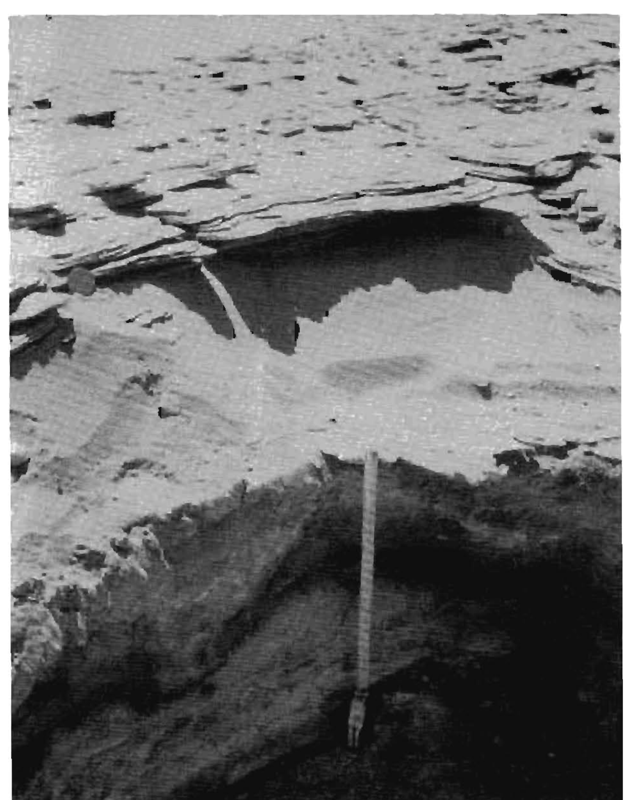

PLATE 3: Weakly cemented laminae of aeolian sands (Unit F) overlying calcreted fluvial sediments (Unit C) at Site 2. Note dark weathering horizon in Unit C.

unit (Plate 2). This weathering is present both where the unit is exposed on today's surface and where it is buried by overlying calcified sands. Although modern rootlets are common in this horizon, the colour remained unchanged after treatment with $H_2O_2$, suggesting a non-organic origin, even though black solonetz soils are common in arid regions where organic matter is mobilised in the presence of alkaline solutions of sodium (Cooke and Warren, 1973). Manganese, and possibly iron, both of which are present today at Gobabeb as aerosols (Annegarn *et al.*, 1978) and in minerals in the local bedrock, may be responsible for the coloration, having been concentrated in this horizon during weathering of the alluvial sediment. Below a depth of about 40 cm from the top of Unit C, the sediment is cemented by an increasing percentage of calcite, rising to 60% at a depth of 60 cm.

In order to form the thick calcrete in the alluvial sediment of Units B and C, wetter conditions than exist in the Khommabes area today, where an average of only 27 mm of rain falls each year, as well as a moderate length of time, would have been necessary.

Goudie (1972) suggests that 250 to 400 mm of rain per annum is favourable for calcrete formation, although the cumulative effects of seasonal, shallow wetting in an arid region of long geomorphic stability should not be discounted (Yaalon and Ward, 1982).

### 4.4 The first aeolian unit

Along the highest margin of the Khommabes deposits (Site 3, Fig. 4), is a well-sorted fine sand, Unit D. The absence of horizontal laminae, low content of mica, good sorting, and elevation above the fluvial units suggest an aeolian origin. This sand may have been deflated from the fluvial deposits, perhaps from a former more extensive Kuiseb River flood-plain, during the soil-forming period previously described. The similarity of quartz roundness and staining in both this unit and Unit C supports this hypothesis. Alternatively, northward migration of the sand sea may have introduced the sand of this unit.

The upper half metre of Unit D has been variably discoloured and mottled a dark brown to dark yellowish brown by iron oxides that have been precipitated during weathering. It seems likely that this weak soil development was contemporaneous with the latter part of the weathering of Unit C — an hypothesis supported by the fact that both units are overlain by the calcareous "crust" of Unit E.

### 4.5 The carbonate crust

A crust of calcite-cemented sand (Unit E) overlies much of the southern part of the Khommabes sediments, where it forms a broken and discontinuous brittle cover, with honeycombed surfaces on both the upper and lower sides of the unit. Its thickness reaches up to 20 cm but varies rapidly over short distances. In some places it is buried beneath Unit F (as at Site 2, Fig. 4). At the sites studied, the quartz sand enclosed in the crust has the same properties as the unit immediately underlying it, and for that reason, it seems that Unit E, in its present state, has formed *in* those units rather than on top of them. The lower boundary is abrupt and overlies carbonate-free sediment in most places.

PLATE 4: Calcified *Phragmites* stems from sands of Unit F at Site 2.

Along the higher elevations of the Khommabes depression, scattered calcified *Phragmites* stems extend upward in the carbonate crust. Elsewhere, there are irregular tubiform shapes scattered throughout the crust, which are possibly related to former roots of the nara (*Acanthosicyos horrida*) plant.

Because of the presence of the calcified *Phragmites* stems, we feel that Unit E was formed by surface or near-surface carbonate precipitation in sand. These plants grow today in locations that remain wet for extended periods of time, such as along the margins of ponded water and at springs and seeps. They can tolerate a salinity of 7 parts per thousand (J.R. Grindley, pers. comm.). In order to establish these plants and to precipitate the calcite of this unit, a number of years of wet conditions in the basin seem necessary.

One possible mechanism for getting water into the basin was for it to percolate into the depression from the Kuiseb River through the transverse dune to the north, perhaps during a period when the level of the river was higher than today. Even recently, open water bodies in the dunes between Swartbank and Rooibank developed by seepage from the Kuiseb River, and lasted for several years after the 1976 and 1978 floods. Similarly, more permanent seepage-fed water bodies occur adjacent to the Uniab, Hoanib, and Hoarusib Rivers in the northern Namib Desert.

Alternatively, an increase in rainfall in the Khommabes area could have been responsible for raising water levels in the basin. A reduction in the evaporation/precipitation ratio by decreasing temperature or increasing cloud cover seems, by itself, to be inadequate to markedly raise moisture levels in the area. If water were actually ponded in the Khommabes depression, which was *not* necessary to precipitate the carbonate and establish plant growth, it would have to have been at least 3.5 m deep to inundate the highest and lowest sites where Unit E is found.

The origin of Unit E is not clear but it seems likely that it has formed either pedogenetically by the downward leaching of carbonate, perhaps from a lacustrine calcite, or by evaporation at the capillary fringe of the ground-water table. The presence of *Phragmites* stems (Plate 4) in their growth position on the higher elevations indicates that any downward translocation of the carbonate into the sandy substrate would have been slight. If the carbonate originated by evaporation of ground-water, the top of the capillary zone must have been at the surface where the *Phragmites* was growing.

The brittle, crystalline nature of the present surface crust has probably formed from the original softer calcium carbonate, which is still preserved where buried (as at Site 2), by a "case hardening" process during downward remobilisation and after exposure at the surface (Goudie, 1973; Lattman, 1977); the honeycomb aspect also probably resulted from the interaction of the crust with moisture and wind after the removal of any overlying poorly cemented sediment. In the arid environment at Khommabes today, this calcite crust forms a resistant cap over the remaining sediments.

The carbonate of "reed casts embedded in crust on the floor" of the Khommabes interdune depression has yielded radiocarbon dates of 27 400 ± 310 (Pta — 2590) and 28 500 ± 370 (Pta — 2591) and, at "slightly higher elevations", of 31 900 ± 460 (Pta — 2588) and 31 600 ± 430 (Pta — 2589) (Vogel and Visser, 1981, p. 77). These dates indicate the time of latest remobilisation of the carbonate in the crust, not the age of its initial deposition, which must be older. Therefore, all sediment below Unit E, as well as the initial wet phase responsible for the carbonate precipitation, is older than 27 000 to 32 000 years.

## 4.6 Calcite-cemented aeolian sediment

Overlying the thin carbonate crust (Unit E) in a number of places across the floor of the Khommabes basin is Unit F, a cross-bedded fine to coarse quartz sand (Plate 2). Most grains are rounded and stained an amber to yellowish red colour, and resemble the modern sands of the Namib Sand Sea. Measured dips of the beds are toward the north-north-east at about 12°. We interpret this sand as being wind-deposited. It seems likely that the margin of the Namib Sand Sea had reached Khommabes at least by this time; we feel that the characteristics of this unit provide the first real evidence for the sand sea at this location.

Individual laminae are variably cemented by calcium carbonate. In places, particularly at the lowest elevations in the northern part of the basin, calcite-cemented tubiform features have been differentially eroded by wind from this unit (Plate 3). Some of these may be root casts of the narra plant and others "calcified termite nest and worm channel" forms (Vogel and Visser, 1981, pp. 76—77).

Radiocarbon dating of the carbonate from some of these tubiform features has yielded dates of 20 900 ± 230 (Pta — 1091) ("root cast"), 21 500 ± 190 (Pta — 2604) ("termite nest") and 22 400 ± 210 (Pta — 2584) ("worm-cast") (Vogel and Visser, 1981, pp. 76—77). The origin of the calcium carbonate of these features and in the enclosing aeolian sand is not clear. Precipitation in a ground-water regime seems likely; airborne carbonate dust may have made contributions. Cementation of the tubiform features may post-date that of the rest of the unit. The radiocarbon dates probably indicate the approximate age of deposition of this aeolian sediment, although the tubiform features (roots and burrows) may have formed in already-cemented sand, having been infilled and cemented at a later time (i.e. at 21 000 to 22 000 yrs. B.P.). The age of the underlying carbonate crust indicates that the aeolian sand of Unit F is probably younger than 27 000 to 32 000 years.

## 4.7 Shaping of the present Khommabes basin

Today, the Khommabes depression is dry and unvegetated. Ground-water levels lie well below its floor. Other than a thin veneer of active aeolian sand, there is no record of deposition since the calcified aeolian sediment of Unit F was emplaced more than 20 000 years ago.

Wind erosion has altered the previous boundaries of the depression and the southern margin now stands above the deflated interdune floor. Very little remains of the stratigraphic sequence, and most of this is capped by a calcareous crust or cemented by calcrete. Fresh granite and schist are exposed on the basin floor, with weathered residues now only present in the more protected localities. Weathering no doubt continues to generate grus from this bedrock — which is then deflated by the wind — in the same way that rock disintegration is occurring elsewhere in the region (e.g. GOUDIE, 1972; SCHOLZ, 1972).

The transverse dune that lies between the Khommabes depression and the Kuiseb River may be partly composed of sand from the dune that passed over the basin 20 000 to 30 000 years ago, depositing Unit F; today only its cemented basal portions remain behind.

## 5 CONCLUSIONS

The Khommabes depression contains deposits representing a long and varied history of sedimentation and secondary alteration. Weathering of the Precambrian bedrock led to the formation of a calcrete-cemented grus (Unit A) below alluvial deposits. The fluvial sediments (Units B and C) were probably deposited on the flood-plain of the Kuiseb River valley, possibly prior to the time when the Namib Sand Sea had advanced this far north — a conclusion based partly on the absence of typical rounded and stained quartz grains that are common in the sand sea. Weathering of the fluvial sediments, under conditions wetter than those of today, developed a second calcrete in the sequence. This has now been altered to a dolocrete in the lower (Unit B) portion. Preserved pedotubules indicate that vegetation grew on the flood-plain. Deflation from the Kuiseb flood-plain, or northward migration of sediment from the sand sea, deposited aeolian sediment (Unit D) on the higher margin of the basin; this may have occurred concurrently with the latter stages of calcrete formation.

Still wetter conditions, or the percolation of water from the Kuiseb River, resulted in deposition of calcite in (or on) the previous sedimentary sequence and the growth of *Phragmites* and other plants. Later recrystallisation of this calcite crust (Unit E) is dated at 27 000 to 32 000 yrs. B.P. Aeolian sediment (Unit F) overlies this calcite crust in places and, because of its similarity to the modern sands of the Namib Sand Sea, represents the oldest certain evidence that the sand sea had reached this area. Dated calcified tubiform structures of biogenic origin in this sand indicate that deposition had occurred by about 21 000 yrs. B.P.

Today, only the basal portions of these dunes and scattered remnants of the older fluvial, aeolian and pedogenic events are found in the Khommabes area. The Kuiseb River is now prevented from flooding the area by the large transverse dune which stretches between the longitudinal dunes on either side of the present depression. Wind continues to erode sediment from the Khommabes sequence, and only the most resistant calcified deposits remain exposed above the interdune floor.

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