

Sedimentary Environments and Trace Fossils of Tertiary Oasis Deposits in the Central Namib Desert, Namibia

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Dish-shaped lenses of dolomitic limestone commonly occur in the arenaceous Lower Tertiary and Quaternary eolianites of the Central Namib Desert region. They are interpreted as the deposits of vegetated playa lakes and, as such, have been described as "fossil oases." Regional stratigraphic studies have shown that there were two separate wet episodes during which these playa lakes formed. These are the Zebra Pan Carbonates of the Late Eocene-Early Miocene Tsondab Sandstone Formation and the Khommabes Carbonates in the partially consolidated Late Pliocene-Recent Sossus Sand Formation.

In plan view, the dolomitic limestone beds have a roughly concentric distribution of lithofacies and trace fossils that reflect the water-table depth and the interaction of the vegetated lake margins with the surrounding dunes. The facies change laterally from outer arenitic dolocrete with branching unlined cylindrical Planolites burrows, some with indistinct meniscæ (possibly Rutichnus) and ovoid Termitichnus nest structures to massive carbonate with desiccation, syneresis, and tepee structures containing abundant Taenidium burrows and reed-stem casts. The central facies comprises microlaminated carbonate with stromatolite mounds and algal matted surfaces with no burrowing in-fauna.

The controlling factor over the stratigraphic distribution of paleo-playas is climate. Both intervals are linked to "wet desert" phases when the climate changed from an arid to relatively wet fluvial phase with perennial rivers and seasonal floods, through to semi-arid, with a more flashy fluvial discharge, and eventually returning to arid conditions. The spatial distribution of these assemblages is controlled by interdune topography and river-flood discharge in the case of the Zebra Pan-type end-point playas, and the elevation of groundwater table by bedrock highs in the case of Khommabes-type oases.

INTRODUCTION

Pans and playas have been identified throughout the world's arid lands as topographic depressions, generally above present groundwater table, that are subject to ephemeral surface-water inundation and to evaporite precipitation in their basal and marginal sediments. Oases are playas with vegetated margins that commonly form in sand-sea deserts. This paper reports the discovery of vegetated paleo-playa deposits, or "fossil oases," in the central

Namib desert of Namibia. Two suites of playa carbonates of different ages have been recognized within semi-consolidated eolianites. These have been the informally named Zebra Pan Carbonates within the Late Eocene-Early Miocene Tsondab Sandstone Formation (Martin, 1957; Ward 1984, 1987) and the Khommabes Pan Carbonates in the Late Pliocene to Recent Sossus Sand Formation (Ward, 1987, 1988; Ward and Corbett, 1990; Fig. 1).

The aims of this study are to describe and map the distribution of sedimentary facies and trace fossils preserved within these exhumed fossil oasis deposits in the central Namib region. Interpretation of these data is assisted by comparison with the deposits of modern playas associated with end-points of ephemeral rivers in the present Namib Sand Sea and other previously described paleo-playa occurrences. It is hoped that this information will help sedimentary geologists recognize paleo-playas in much older successions, in limited exposures and borehole cores, and, thus, refine their paleoenvironmental interpretations.

The distribution of both carbonate suites—the Zebra Pan-type and the Khommabes-type in the hyperarid central Namib region—and the location of the outcrops used in this study are illustrated in Figure 2. To date, 25 Khommabes-type carbonate outcrops have been mapped in interdunes of the northern Namib sand sea (Sossus Sand Fm.) and 10 Zebra Pan-type occurrences in outcrops of the Tsondab Sandstone. For the past 20,000 years, irregular flash flooding of the westerly flowing Kuiseb River has effectively prevented the dunes on the south bank of the Namib Sand Sea from migrating onto the gravel plains to the north. During this period, continued downwasting of the semi-consolidated eolian sandstones of the Tsondab Sandstone Formation has completely exhumed some of the resistant Zebra Pan-type carbonate bodies, which now occur as a caprock on low mesas.

DESCRIPTION AND INTERPRETATION OF ZEBRA PAN-TYPE CARBONATES

The overall geometry of Lower Tertiary Zebra Pan-type carbonates is distinctively dish-shaped (concavo-convex as in Fig. 3) and lenticular in cross-section. The carbonate beds all dip between 20–30° towards the central and lowest part of the outcrop. Facies transitions and bedding thicknesses confirm that this is close to the original gradient of the margins of a nearly circular depression. The carbonates form relatively small outcrops, generally less than 1 km², and their distinctive light gray color stands out against the reddish-brown Tsondab sandstones (Fig.

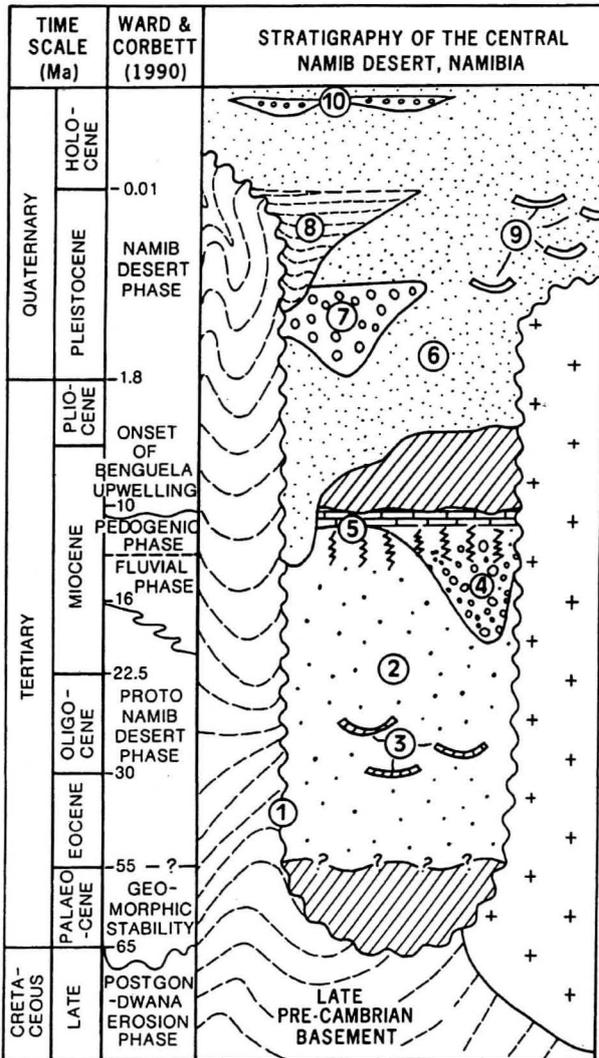


FIGURE 1—Summary of the stratigraphy of the Central Namib Desert, Namibia. (1) Post-Gondwana erosion surface- the Namib Unconformity Surface (Ollier, 1977). (2) Tsondab Sandstone Formation- eolianites. (3) Zebra Pan Carbonate Member- paleo-playa carbonates. (4) Karpfenkliff Conglomerate Formation- alluvial fans as a result of increased rainfall. (5) Kamberg Calcrete Formation- geomorphic stability and pedogenesis. (6) Sossus Sand Formation—arid eolian sand sea. (7) Oswater Conglomerate Formation- fluvial incision. (8) Homeb Silt Formation- fluvial aggradation. (9) Khommabes Carbonate Member- fossil "oases" (10) Gobabeb Gravel Formation- fluvial incision.

3). Detailed mapping of one of the Zebra-Pan type exposures (S 23° 24.294' ; E 15° 47.777' on the farm Oase) bordering the Namib Naukluft National Park (Figs. 2 and 3) revealed 4 distinctive sedimentary facies, 3 of which are concentrically disposed in a bullseye pattern that reflects their distribution in the original playa lake (Fig 4). Erosion of the margins during and after exhumation has removed some, but not all, of the peripheral facies and has sculpted the outcrop into its present trifid footprint shape from its original circular plan. The facies distributed along the preserved outer margin of the playa comprises sandy

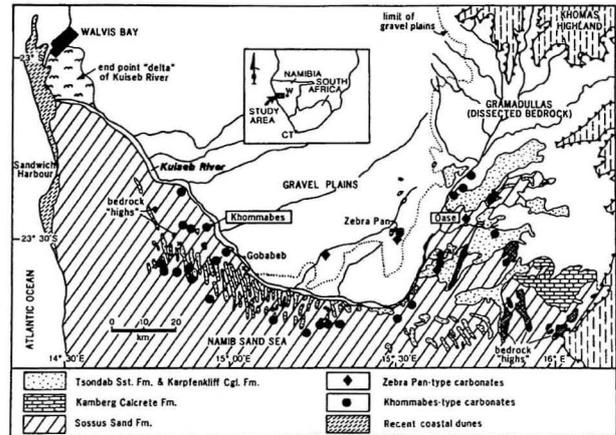


FIGURE 2—Geological map of the Central Namib Desert Region showing the distribution of paleo-playa carbonates and location of the Oase and Khommabes outcrops.

carbonate rock with some cross-bedding, which we term the arenitic carbonate facies. The inner slopes are composed of massive carbonate characterized by desiccation features, while the center of the dish-shaped outcrop contains a microlaminated carbonate facies with stromatolite domes. A channel-fill conglomerate comprises the fourth facies. It fills a single channel on the northern margin of the outcrop that has been eroded into the outer arenitic carbonate.

Following is a brief summary of the lithology, sedimentology, and ichnology of the Zebra Pan facies mapped at Oase (Fig. 4). Measured section logs (Fig. 5) show the sedimentary sequences from the periphery of the outcrop. No sections could be measured in the center. The most notable section is log A where the channel facies is recorded. A single log of a small outlier of this outcrop, some 500 m away, was also included (Fig. 5E).

Arenitic Dolocrete Facies

Description

Originally, this facies was more widespread and now is preserved only as remnants on the eroded periphery of the outcrop (Fig. 4). It is composed of medium- to coarse-grained sandstone with a calcite cement. In hand specimen, the rock is light red (2.5YR 6/6) with white specks, and the wind has etched a rugged, pitted surface. In thin section the carbonate contains grains of reddish-brown, well-sorted and rounded sand that float in a micrite groundmass. Ward (1987) estimated the composition of this facies as 40% calcite, 40% detrital quartz, and 20% dolomite.

The absence of bedding may be due to intense bioturbation, which has left very little of the sediment disturbed. Branching, cylindrical burrows are orientated both horizontally and vertically, and are 2–3.5 cm in diameter. The walls of some of these burrows are preserved. They are infilled with structureless terra rosa colored sandstone although menisci are visible in a few specimens. The size, infill structures, and branching characteristics of these bur-



FIGURE 3—Aerial view of the exhumed Zebra Pan Carbonate occurrence at Oase showing the light gray, dish-shaped limestone body capping a low mesa of Tsondab Sandstone eolianites.

rows are characteristic of *Rutichnus* (D'Alessandro et al., 1987; Keighley and Pickerill, 1994) and are attributed to termites and beetles (Ratcliffe and Fagerstrom, 1980; Noiro, 1970).

Interpretation

The arenitic dolocrete facies is interpreted as an interdune playa carbonate that was periodically inundated and exposed. Eventually, it was buried under migrating sand dunes. The interplay between eolian and lacustrine sedimentation reflects a marginal playa setting, but its lack of bedding and desiccation features indicates that it was not subaerially exposed for prolonged periods. The degree of dolomite cementation and intense burrowing is similar to groundwater dolocretes described by Colson and Cojan (1996) from the Oligocene Provence basin of France. These dolocretes are interpreted as having been precipitated in the phreatic zone around a playa lake. As the lake level is lowered by strong evaporation, the saline lake waters infiltrate the burrowed sands around the lake and mix with fresh groundwater flowing into the playa, causing the precipitation of interstitial dolomite.

Massive Carbonate Facies

Description

This facies consists of light gray (10YR 7/2), massive microcrystalline carbonate with vague and impersistent horizontal laminae and lenticular beds of grainstone conglomerates. This facies occurs in the upper half of the section overlying the microlaminated carbonate in the periphery of the outcrop (Fig. 5B-D). Ward (1987) identified the dominant mineralogy at the Zebra Pan type locality as 80–85% dolomite. Alizarin-red stained and polished sections from the study outcrop confirm that the groundmass is composed of microcrystalline dolomite with matrix-supported grains of poorly-sorted angular quartz and a few rounded rock fragments. Ward (1987) noted lenticular gypsum-crystal casts in the dolostones at the Kamberg locality, a feature that we also have identified at the Oase locality (Fig. 6) along with lath-shaped crystals of anhydrite and

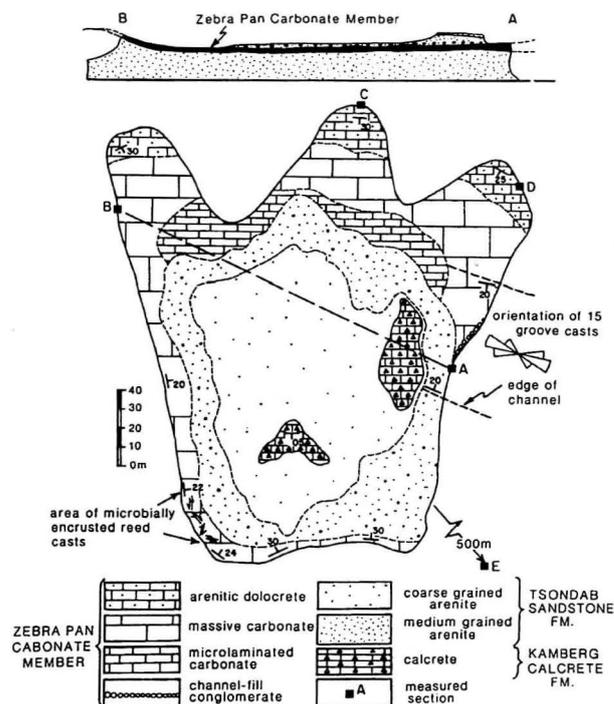


FIGURE 4—Cross-section and map of the Zebra Pan Carbonate Member on Oase showing the roughly concentric distribution of lithofacies.

lutecite nodules (length-slow chalcedony). The presence of lutecite indicates that some diagenetic replacement of evaporite minerals by silica has occurred (Folk and Pittman, 1971).

Weathered surfaces of the massive carbonate facies typically have karstic clints and grikes caused by widening of joints. Bedding-plane exposures commonly display a regular pattern of decimeter-scale polygonal shrinkage cracks with slightly upturned edges, filled with buff-colored calcareous arenite (Fig. 7). A variant of shrinkage cracking is a cm-scale rectilinear pattern of sand-filled cracks that taper in width in all directions (Fig. 8). These cracks are indicative of syneresis-induced shrinkage. In some cases, biologic activity has influenced the pattern of shrinkage cracks. This is particularly evident in those that radiate from sinuous trails and circular indents made by footprints. The undersurface traces clearly show both concentric and radial crack pattern.

In some cliff-section exposures, the crystallization of carbonate minerals between bedding planes has caused buckling of the entire section into whaleback mounds with tepee structures in their axes. These whalebacks are spaced approximately 5 meters apart.

Large (5–8 mm diameter), branching burrow systems filled with light reddish-brown well-sorted and well-rounded medium-grained sand are a distinctive feature of this facies (Fig. 9A). The burrows are unlined and are oriented both horizontally and vertically with more bifurcations in the horizontal systems. Based on the observation that these burrows are unlined and generally lack menisci, they are identified as *Planolites*. The few unbranched

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| Humid Tropical soils are (a) shallow, (b) calcium rich, (c) both or (d) neither | <input type="checkbox"/> |
| Los Angeles gets its water from (a) The Ocean, (b) Mexico , (c) Sierra Nevada, (d) Las Vegas | <input type="checkbox"/> |
| Jakobshaven Glacier is located (a) Antarctica, (b) Greenland, (c) Iceland, (d) Russia , (e) Canada | <input type="checkbox"/> |
| Which of these is not a polar orbiter a) Landsat b) Meteosat c) Spot d) MODIS e) Ikonos | <input type="checkbox"/> |
| Climatic aridity is caused by (a) high pressure cells, (b) convergence, (c) neither, (e) both | <input type="checkbox"/> |
| Which soils are found in the Arid Tropics (a) Oxisols, (b) Mollisols, (c) Gelisols, (d) Ultisols | <input type="checkbox"/> |
| One polar orbit takes (a) 90 minutes , (b) 24 hours, (c) 12 hours, (d) 60 min to complete | <input type="checkbox"/> |
| Northern Namibia occupies which river basin (a) Fish River, (b) Cunene, (c) Orange , (e) Limpopo | <input type="checkbox"/> |
| Which is the biggest global fresh water store (a) rivers, (b) lakes, (c) groundwater, (d) plants | <input type="checkbox"/> |
| Which of these does not reach the ocean (a) Orange, (b)Limpopo, (c) Okavango, (d) Cunene, | <input type="checkbox"/> |
| Sea level rise is indirectly caused by melting of (a) glaciers, (b) icecaps, (c) permafrost | <input type="checkbox"/> |
| Which is the shorter wavelength region (a) thermal, (b) near IR, (c) UV (d) visible | <input type="checkbox"/> |
| Which one has the lowest spatial resolution (a) Landsat, (b) Ikonos, (c) Spot, (d) MODIS | <input type="checkbox"/> |
| Which country does not have permafrost a) Canada, (b) US, (c) Holland, (d) China, (e) Russia | <input type="checkbox"/> |
| Name 4 countries in the Sahel Region _____ | <input type="checkbox"/> |
| Aridsols are (a) rich in iron, (b) calcium, (c) , organics (d) none of these, (e) loess | <input type="checkbox"/> |
| What is the current annual rate in sea level rise (a) +1, (b) +3, (c) +5, (d) +7, (all in mm) | <input type="checkbox"/> |
| Where is the ITCZ in January (a) equator, (b) northern hemisphere, (c) southern hemisphere | <input type="checkbox"/> |
| What percentage fresh water is not frozen: (a) 10 % , (b) 30% , (c) 50% , (e) 70%, (f) 90% | <input type="checkbox"/> |
| The largest cause of Amazon deforestation is (a) ranching, (b) logging, (c) agriculture, (d) mining | <input type="checkbox"/> |

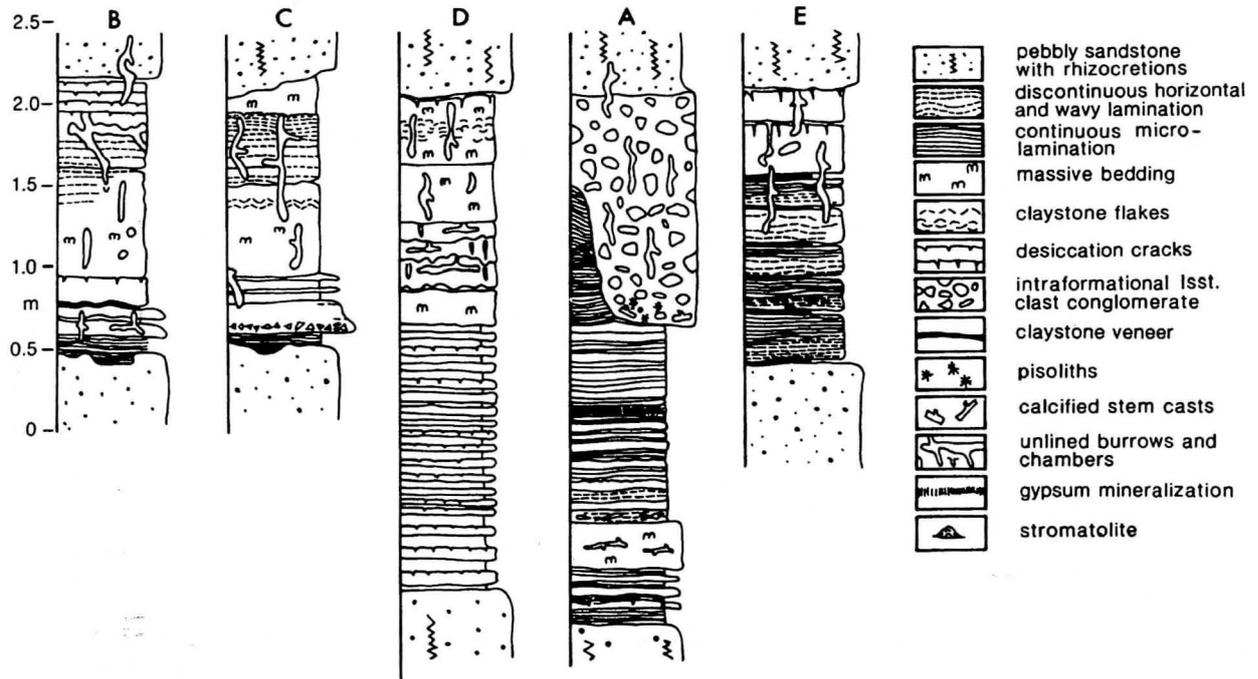


FIGURE 5—Outcrop sections of the Zebra Pan Carbonate on Oase (refer to Fig. 4 for section localities).

burrows that do show meniscate backfill are assigned to the ichnogenus *Taenidium* (Fig. 9B). *Planolites* and *Taenidium* burrows probably were formed by burrowing insects such as beetles and termites (Smith et al., 1993). In one instance, laminated red claystone veneers were observed lining the floor of a horizontal tunnel. This indicates that parts of the burrow system remained open for a

some time before being passively filled with windblown sand and, as such, cannot be assigned to *Planolites*.

Close inspection of many of the smooth bedding planes reveals clumps of vertical to sub-vertical straight tubes about 1 mm diameter, composed of microcrystalline calcite and filled with equant calcite crystals. These are interpreted as clumps of calcified stems of charophytic algae. In places, the massive carbonate rock displays a spongy fenestrate texture of interconnecting mm-diameter channels. This texture is interpreted as algal filament mats similar to those described by Düringer and Gall (1994) in Oligocene strata of the Rhine rift-graben system of western Europe. Rarely, isolated plano-convex stromatolite domes occur in this facies. They appear to be preserved in life position, have basal diameter circa 10 cm, and display mm-scale crenulated microlaminae.

A 200-m² area in the southeastern corner of the outcrop is rich in fossil reeds (*Phragmites*), which presumably grew around the playa margin (Fig. 4). In this reed bed, the massive carbonate is packed with ribbed stem casts, each of which is enveloped in a microbial encrustation (Fig. 9C). The stem casts are cylinders of structureless sandstone, 1–5 cm in diameter, with distinct longitudinal striations on their outer surface. Each stem is surrounded by a 1-to-1.5-cm-thick layer of densely-packed microtubules which looks spongy in cross section and matted in longitudinal section. Each tiny tubule (0.5–1.25 mm in diameter) has a calcareous lining and sometimes shows horizontal connections with adjacent tubules (Fig. 9D). The circumferential growth habit and orientation of the tubules along the stem indicates that the microbial growth took place when the reed stem was upright and most probably living. These encrustations are attributed to the col-

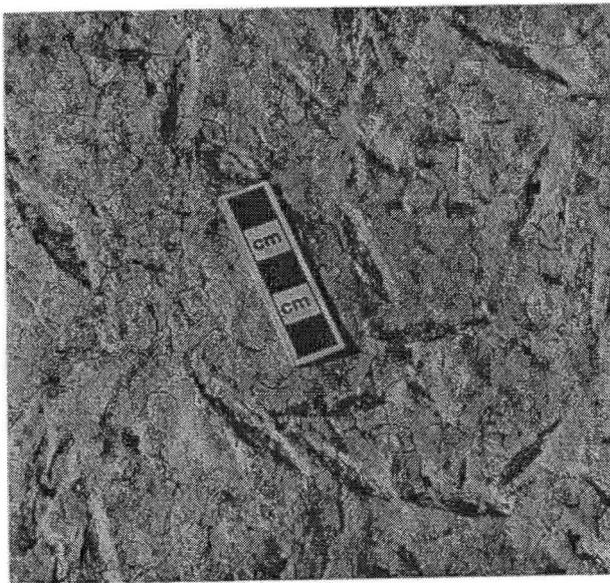


FIGURE 6—Casts of gypsum laths in the massive carbonate facies of Zebra Pan Carbonate Member at Oase.

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| Northern Namibia occupies which river basin (a) Fish River, (b) Cunene, (c) Orange , (e) Limpopo | <input type="checkbox"/> |
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| Aridsols are (a) rich in iron, (b) calcium, (c) , organics (d) none of these, (e) loess | <input type="checkbox"/> |
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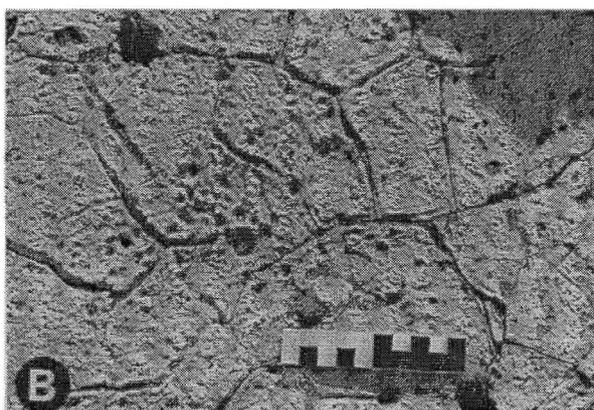


FIGURE 7—Exhumed surface of the Zebra Pan massive carbonate facies with close-up of desiccation cracks showing upturned edges typical of algal mats. Scale in cm.

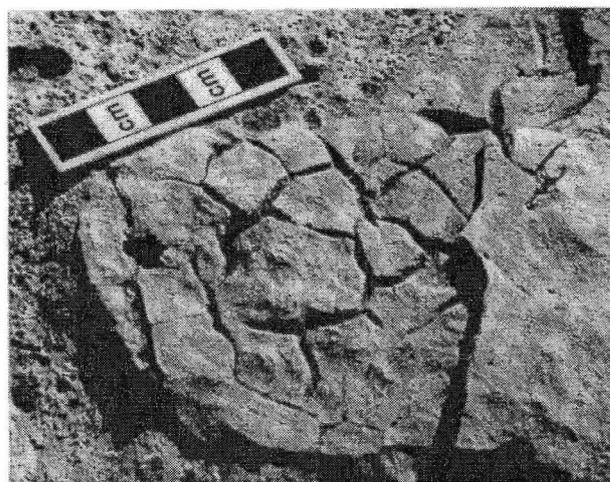


FIGURE 8—Syneresis shrinkage cracks in massive carbonate of the Zebra Pan Carbonate Member at Oase.

onization of the predominantly submerged portions of upright reed stems by commensal microbial organisms (Düringer and Gall, 1994) and charophytes. This colonization occurs quite rapidly and continues throughout the life of the plant.

Cut-and-polished surfaces show that the microbial encrustation also occurs as broken fragments that have been cemented by later growth. The smooth, sharp base of the encrustation defines the outer stem surface, and the light brown sandy pith cast defines the ribbed inner surface of the stem wall. The pith cavities of some horizontal stems are only partially filled with sand, indicating that the toppled reeds had rigidity imparted by both the sclerenchymatous fiber bundles in the stem wall and the calcareous encrustation. In support of the latter interpretation, broken fragments of the encrustation that have been incorporated in later encrustation show brittle fractures that indicate contemporaneous biomineralization was taking place.

On the outer edge of the reed bed, the host limestone is brecciated and the matrix is more porous than in the center. Here, the microbial epibionts form a crenulated encrustation around horizontal stems, which are geopetally infilled with sand. Some horizontal stem casts are filled with a basal medium-grained sand topped by a layer of micrite followed by an upper layer of fine sand and, in some cases, a micrite-lined cavity. This compound geopetal fill reflects the interplay between eolian, lacustrine, and pedogenic processes that is characteristic of marginal playa environments.

Bedding-plane exposures at the Zebra Pan type locality display a series of large, circular depressions, 20–25 cm in diameter, filled with concentrically layered, thinly bedded carbonate with radial and concentric cracks. Vertical sections through these structures show them to be indented footprints (Fig. 10; Allen, 1989; Loope, 1986; Lea, 1996). Some 20 cm below the surface, the carbonate beds form a gently indented underprint. The overlying layers have all been ruptured by the weight of a medium-sized quadruped.

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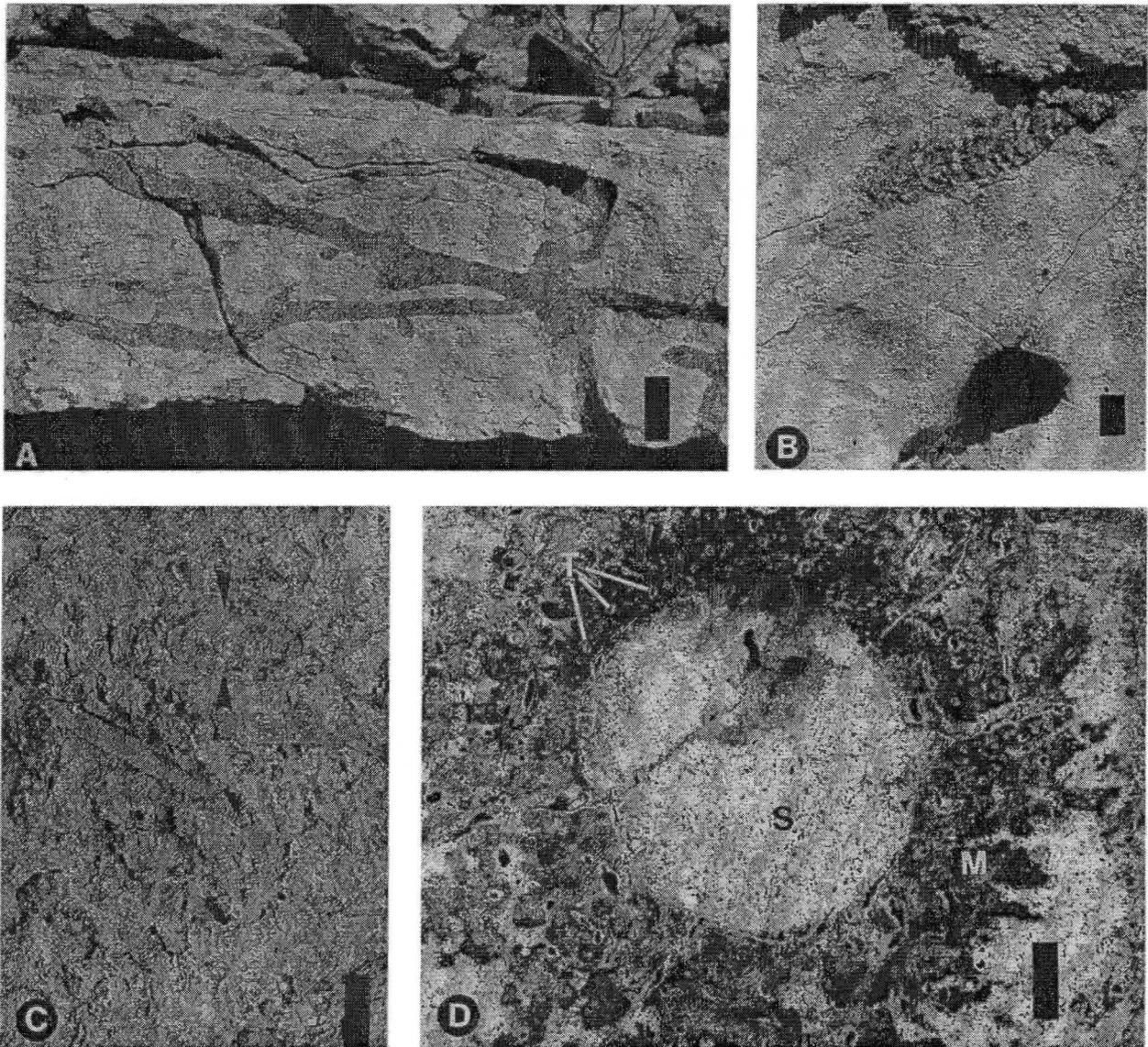


FIGURE 9—Trace fossils of Zebra Pan type carbonates (A) Unlined *Planolites* burrows filled with structureless sand in the massive carbonate facies of the Zebra Pan Carbonate on Oase. Scale bar = 2 cm. (B) *Taenidium* burrows showing meniscate backfilling in massive carbonate muds of the Zebra Pan outcrop. Scale bar = 1 cm. (C) A patch of microbially encrusted reed-stem casts preserved in the massive carbonate facies of the Zebra Pan outcrop on Oase. Arrowheads indicate stem cast in life position. Scale bar = 2 cm. (D) Cross section through one of the microbially encrusted (M) sandstone filled (S) reed stems shown in Figure 11. Note the numerous tiny calcite lined tubules (T) within the microbial mass. Scale bar = 5 mm.

Interpretation

The density of stem casts in the fossil reed bed indicates that reeds grew in saturated sediments, either a wetland or in shallow water along one side of the playa lake. Periodic lowering of the water level exposed the microbially encrusted bases of the reeds to dehydration and subaerial weathering. Fragments of calcareous charophyte tubes accumulated at the base of the stems and were recemented by renewed microbial growth when the water level rose again. During lowstand, the newly exposed lime muds

gradually desiccated, and at least two generations of polygonal mudcracks opened up and trapped windblown sand in the fissures. At this time beetles and termites colonized the newly drained mud flats and dug branching burrow networks down to the water table, parts of which were backfilled (*Taenidium*), the bulk remaining open to be passively filled by windblown sand and leached clay.

Large quadrupeds, such as elephant, gemsbok, and wildebeest, walked across this area to drink at the shrinking water body, leaving their footprints deeply impressed in the soft, lime-rich mud beneath the surface crust. Sheet

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| Which of these is not a polar orbiter a) Landsat b) Meteosat c) Spot d) MODIS e) Ikonos | <input type="checkbox"/> |
| Climatic aridity is caused by (a) high pressure cells, (b) convergence, (c) neither, (e) both | <input type="checkbox"/> |
| Which soils are found in the Arid Tropics (a) Oxisols, (b) Mollisols, (c) Gelisols, (d) Ultisols | <input type="checkbox"/> |
| One polar orbit takes (a) 90 minutes, (b) 24 hours, (c) 12 hours, (d) 60 min to complete | <input type="checkbox"/> |
| Northern Namibia occupies which river basin (a) Fish River, (b) Cunene, (c) Orange, (e) Limpopo | <input type="checkbox"/> |
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| Which of these does not reach the ocean (a) Orange, (b) Limpopo, (c) Okavango, (d) Cunene, | <input type="checkbox"/> |
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| Which country does not have permafrost a) Canada, (b) US, (c) Holland, (d) China, (e) Russia | <input type="checkbox"/> |
| Name 4 countries in the Sahel Region _____ | <input type="checkbox"/> |
| Aridsols are (a) rich in iron, (b) calcium, (c) , organics (d) none of these, (e) loess | <input type="checkbox"/> |
| What is the current annual rate in sea level rise (a) +1, (b) +3, (c) +5, (d) +7, (all in mm) | <input type="checkbox"/> |
| Where is the ITCZ in January (a) equator, (b) northern hemisphere, (c) southern hemisphere | <input type="checkbox"/> |
| What percentage fresh water is not frozen: (a) 10%, (b) 30%, (c) 50%, (e) 70%, (f) 90% | <input type="checkbox"/> |
| The largest cause of Amazon deforestation is (a) ranching, (b) logging, (c) agriculture, (d) mining | <input type="checkbox"/> |
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floods at the onset of the rainy season swept blocks of desiccated mud and dead reed stems into shallow depressions on the shoreline to be preserved as limestone breccia.

Microlaminated Carbonate Facies

Description

The limestone becomes microlaminated towards the center of the dish-shaped Oase outcrop (see Fig. 4). This same facies is encountered at the base of all the sections measured around the margin of the Oase outcrop (Figs. 5 and 10B), which indicates that it was more widespread when the lake first formed at this site. It comprises a 0.2–1.4-m-thick succession of thinly-bedded microlaminated dolomite. The microlaminae are defined by millimeter-thick, light gray dolomiticrite/dark gray siltstone couplets with dark gray stringers that display distinctive stromatolite-like wrinkles and domes. Bioturbation is limited to isolated, sand-filled, narrow (2 mm diameter), sub-vertical tubes. In places, the wavy microlaminae are deflected downwards into the tubes, suggesting that these are short vertical burrows, possibly *Cylindricum*. The cream-colored dolo-micrite is considered to be a secondary diagenetic alteration of primary gray carbonate; it forms a halo around all the burrow structures, indicating that they probably were a conduit for pore waters during diagenesis. Isolated lenses of fine-grained arenite occur sporadically throughout this facies.

Interpretation

The microlaminated carbonate is interpreted as the deeper water (>0.5 m and <5 m) facies of a playa lake that was subject to long dry periods between infrequent flood events. Each siltstone/carbonate couplet resulted from a single pulse of sedimentation followed by a hiatus, during which calcium carbonate was precipitated by evaporative concentration at the sediment-water interface (Clemmensen, 1978; Wright and Platt, 1995). The dolomitization occurred soon after burial, before compaction, and probably was the result of evaporative pumping (Colson and Cojan, 1996). During major sandstorms, eolian dust was blown into the central parts of the lake and settled through the water column to form the irregular patches of arenite within this facies. The dark gray stringers are interpreted as the organic remains of algae that grew on the sediment/water interface, and possibly also played a role in the precipitation of carbonate (Dean and Fouch, 1983). In some parts of the lake, sedimentation was slow enough to allow successive mats to build domal algal stromatolites. The occurrence of these deeper water facies at the base of the marginal sections indicates that the lake was much larger when it first formed.

Channel-fill Conglomerate

Description

On the northern side of the Zebra Pan Carbonate outcrop on Oase, the microlaminated facies is cut by a single channel filled with matrix-supported, limestone cobble and pebble conglomerate (Fig. 5A). There is no evidence of the channel on any of the other margins of the outcrop,

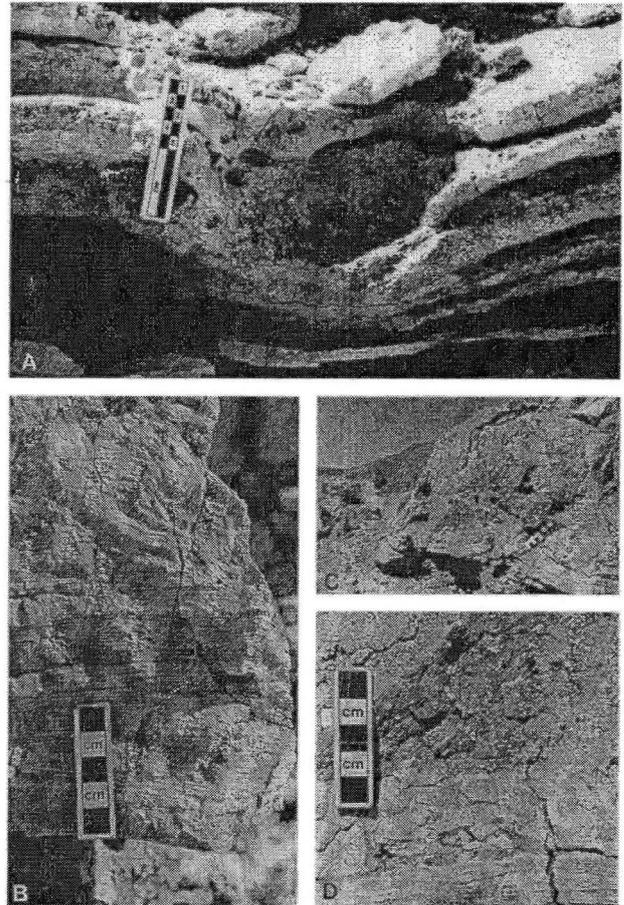


FIGURE 10—Zebra Pan Carbonate sediments and trace fossils. (A) Vertical section through an elephant (?) footprint that was imprinted into the plastic carbonate mud in the shallows around the margins of the Zebra Pan paleo-playa on Oase. (B) Microlaminated carbonate facies at the base of the Zebra Pan Carbonate on Oase. (C) Outcrop view and (D) close up of the fluvial channel entering the Zebra Pan Carbonate on Oase. The channel base was eroded into semi consolidated microlaminated carbonate mud and filled with angular carbonate mud clasts "floating" in a groundmass of eolian sand.

leading to the conclusion that it represents an end-point playa fed by seasonal floods from an ephemeral river. Shallow, sand-filled runnels on the basal surface and the strike of the gently dipping (20°) margins of the channel show that the flow came from the northwest. The channel cross-section is approximately 60 m wide and 0.8 m deep with a smooth basal erosion surface (Fig. 10C, D). The channel fill lacks internal bedding and comprises a massive, matrix-supported conglomerate of subrounded, flattened biscuits of massive carbonate, up to 16 cm diameter and 2.5 cm thick, along with fragments of calcified rhizcretions and pisoliths. Abundant, small, angular fragments of the underlying laminated carbonate facies are common (Fig. 10C, D).

Extensive branching burrows have penetrated this facies from the overlying Tsondab eolianite. They are a complex system of horizontal chambers or galleries about 1.5 cm wide and 20 cm long connected by subhorizontal cylin-

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| Northern Namibia occupies which river basin (a) Fish River, (b) Cunene, (c) Orange , (e) Limpopo | <input type="checkbox"/> |
| Humid Tropical soils are (a) shallow, (b) calcium rich, (c) both or (d) neither | <input type="checkbox"/> |
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| Los Angeles gets its water from (a) The Ocean, (b) Mexico , (c) Sierra Nevada, (d) Las Vegas | <input type="checkbox"/> |
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| Which of these is not a polar orbiter a) Landsat b) Meteosat c) Spot d) MODIS e) Ikonos | <input type="checkbox"/> |
| Which is the biggest global fresh water store (a) rivers, (b) lakes, (c) groundwater, (d) plants | <input type="checkbox"/> |
| Which country does not have permafrost a) Canada, (b) US, (c) Holland, (d) China, (e) Russia | <input type="checkbox"/> |
| Name 4 countries in the Sahel Region _____ | <input type="checkbox"/> |
| Which one has the lowest spatial resolution (a) Landsat, (b) Ikonos, (c) Spot, (d) MODIS | <input type="checkbox"/> |
| Sea level rise is indirectly caused by melting of (a) glaciers, (b) icecaps, (c) permafrost | <input type="checkbox"/> |
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| What percentage fresh water is not frozen: (a) 10 % , (b) 30% , (c) 50% , (e) 70%, (f) 90% | <input type="checkbox"/> |
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| Aridsols are (a) rich in iron, (b) calcium, (c) , organics (d) none of these, (e) loess | <input type="checkbox"/> |
| Where is the ITCZ in January (a) equator, (b) northern hemisphere, (c) southern hemisphere | <input type="checkbox"/> |
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drical tunnels from 0.8 cm–1.5 cm in diameter. The tunnels and chambers are passively filled with eolian sand similar to the overlying Tsondab Sandstone.

Interpretation

The Zebra Pan carbonate mud-clast conglomerate demarcates the infilled input channel of an endpoint playa. The intraclasts were locally eroded from the edge of the playa, transported a short distance, and dumped in a shallow scour trough. The matrix supported fabric indicates that the dominant depositional process was a series of high-density debris flows. The open U-shaped cross-section and poorly-sorted melange of locally derived clastics that fill this channel indicate that it was cut and filled in the same short-lived flood event. The lack of an exit channel from the lake depression suggests that the playa was at an end-point of an ephemeral stream in the Tsondab Sand Sea which was periodically rejuvenated by floodwaters, a setting similar to Sossusvlei on the eastern margin of the present Namib Sand Sea. Termites and beetles colonized this sediment between floods and especially after final abandonment. Most of the chambers and tunnels were passively filled with eolian dust as the entire playa system became overwhelmed by the advancing dunes.

Depositional History of the Zebra Pan Carbonate

The four facies recognized within the dish-shaped Zebra Pan Carbonate occurrences are interpreted as having been deposited in an end-point playa of small distributary rivers that underwent slow, but continuous drying-out. The outer arenitic carbonate represents a peripheral lacustrine or palustrine (Platt, 1989) environment. The inner massive carbonate was submerged for much of the time, but periodically desiccated with synaeresis shrinkage under shallow-water conditions; subaerial desiccation occurred only for the short periods when the lake dried out completely. The central microlaminated facies accumulated under more or less permanent standing water. The channel-fill facies is interpreted as the preserved portion of a distributary channel that regularly (perhaps seasonally) rejuvenated the playa with floodwater. The microbially encrusted reed stems in the periodically desiccated massive carbonate facies indicate that shallow water (5–10 cm) persisted in this part of the depression long enough for cyanophytes and calcareous algae to build up colonies around the submerged portion of the stems and on the lake bed. This indicates that periods of exposure and desiccation were generally short and not necessarily seasonal. Marginal sediments clearly remained moist long enough for reed beds to establish mature plants, and standing water conditions existed long enough for adult plants to be microbially encrusted. Thus, it is concluded that the Zebra Pan end-point depressions were vegetated for much of the year and, as such, they could be described as fertile playas or oases.

DESCRIPTION AND INTERPRETATION OF KHOMMABES-TYPE CARBONATES

Khommabes is one of at least twenty-five, small areally-restricted carbonate occurrences associated with cement-

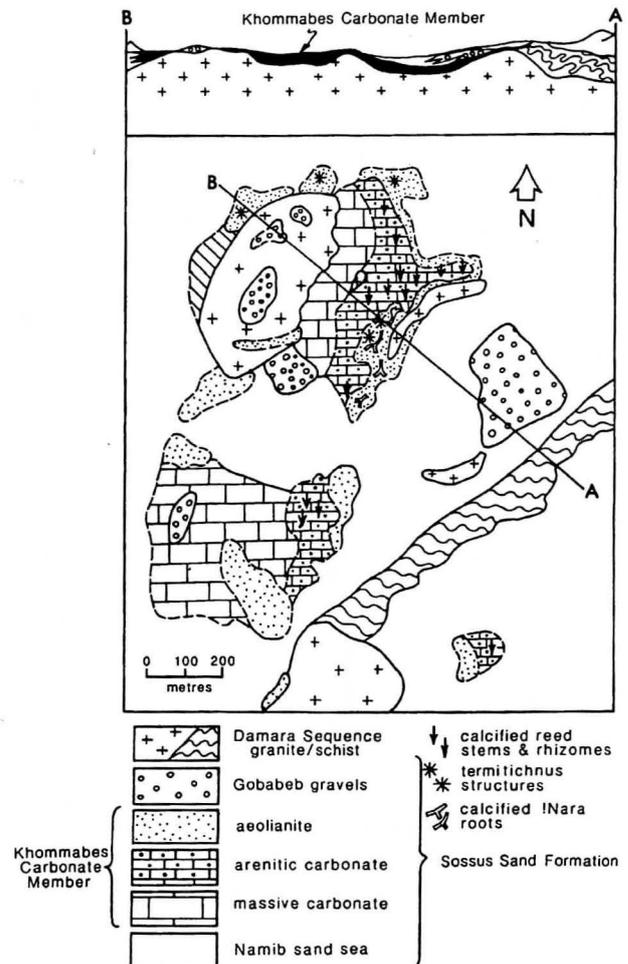


FIGURE 11—Vertical and planimetric distribution of lithofacies and trace fossils in the Khommabes Carbonate Member outcrop at Khommabes.

ed eolianites of the Namib Sand Sea (Sossus Sand Formation) in the central Namib desert (Ward, 1984, 1987; Fig. 2). They are of interest for a number of reasons: (1) they record a period of wetter climate during the recent history of the Namib about 22,000 years ago (Vogel and Visser, 1981); (2) they contain floral and faunal remains; and (3) they are good collecting sites for human artifacts.

The Khommabes locality lies 6 km NW of Gobabeb (S23° 32'; E14° 59') and 1.5 km south of the Kuiseb River within an interdune area of the modern Namib desert. The paleo-playa, which has an area of some 3 km² (Fig. 11) and is less than 2 m thick, was formed around three granitic bedrock highs. The southern bedrock high forms a prominent northeast-southwest-trending ridge that probably formed a physical barrier to groundwater movement, causing water to pond on the surface at this site. There is no evidence of an input channel. The two northern outcrops are low domes and reflect the topography of the eroded post-Gondwanan landscape. Unlike the Zebra Pan exposures, the Khommabes-type deposits never topographically inverted

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| Which soils are found in the Arid Tropics (a) Oxisols, (b) Mollisols, (c) Gelisols, (d) Ultisols | <input type="checkbox"/> |
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| Humid Tropical soils are (a) shallow, (b) calcium rich, (c) both or (d) neither | <input type="checkbox"/> |
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| Which of these is not a polar orbiter a) Landsat b) Meteosat c) Spot d) MODIS e) Ikonos | <input type="checkbox"/> |
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| Which country does not have permafrost a) Canada, (b) US, (c) Holland, (d) China, (e) Russia | <input type="checkbox"/> |
| Which is the biggest global fresh water store (a) rivers, (b) lakes, (c) groundwater, (d) plants | <input type="checkbox"/> |
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| Sea level rise is indirectly caused by melting of (a) glaciers, (b) icecaps, (c) permafrost | <input type="checkbox"/> |
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| What is the current annual rate in sea level rise (a) +1, (b) +3, (c) +5, (d) +7, (all in mm) | <input type="checkbox"/> |
| Aridsols are (a) rich in iron, (b) calcium, (c) , organics (d) none of these, (e) loess | <input type="checkbox"/> |
| The largest cause of Amazon deforestation is (a) ranching, (b) logging, (c) agriculture, (d) mining | <input type="checkbox"/> |
| Where is the ITCZ in January (a) equator, (b) northern hemisphere, (c) southern hemisphere | <input type="checkbox"/> |
| Name 4 countries in the Sahel Region _____ | <input type="checkbox"/> |
| What percentage fresh water is not frozen: (a) 10%, (b) 30%, (c) 50%, (e) 70%, (f) 90% | <input type="checkbox"/> |

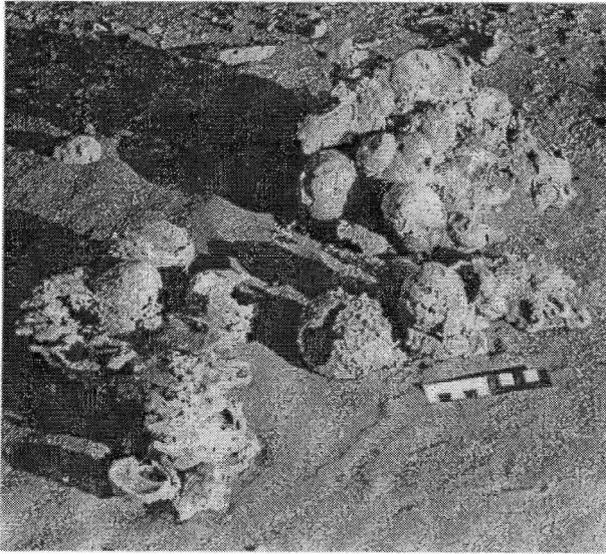


FIGURE 12—Exhumed clusters of calcified termitaria calies (*Termitichnus*) from the Late Pleistocene Khommabes Carbonate Member. Scale in cm.

by downwasting and are commonly concealed by the unconsolidated sand of the Sossus Sand Formation and slightly older, coarser-grained Gobabeb Gravels. As with the Zebra Pan Carbonates, this locality displays a similar concentricity of sedimentary facies. The outermost facies is a cemented eolianite with terrestrial trace fossils. It surrounds a zone of arenitic carbonate with *in situ* plant remains that, in turn, surrounds an innermost massive carbonate facies.

Eolianite Facies

Description

The eolianite facies comprises light red (10YR6/8) fine- to medium-grained, partially consolidated sandstone that contains well-sorted, well-rounded grains and is coated with a desert varnish. High-angle planar cross-beds, which are the main structure, indicate that southerly winds were dominant in the Late Pleistocene (Ward et al., 1983). The peripheral outcrop pattern of this facies (Fig. 11) shows that the sediment was laid down in a dish-shaped depression. It owes its preservation to the protection provided by carbonate cementation of the overlying arenitic carbonate facies. Wind etching of the preferentially calcified foreset beds has enhanced the visibility of the eolian cross bedding.

Unusual carbonate-cemented ovoid structures and branching tubes are preserved between the foresets. These were documented by Ward (1984) as fossil termite nests and pedotubules, respectively. The nest structures occur in two forms: (1) ovoid calies, comprising solid outer shells, completely or incompletely preserved (Fig. 12), with either a structureless or burrowed sandstone filling (Fig. 13A–D); and (2) tunnel complexes comprising networks of interconnecting calcite-lined tunnels that radiate away from a central vertical axis (Fig. 14).

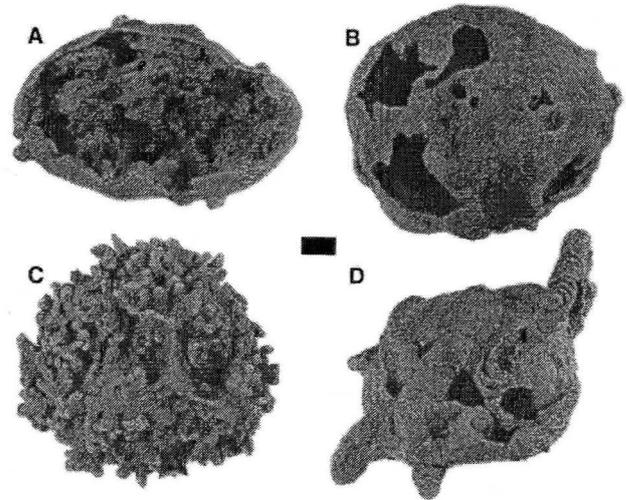


FIGURE 13—A selection of ovoid *Termitichnus* structures from the eolianite facies of the Khommabes Carbonate Member. (A) Solid outer wall with burrow network inside. (B) Solid outer wall without burrow network inside. (C) Spherical *Termitichnus* nest of radially disposed calcite-lined tunnels. (D) Ovoid *Termitichnus* calie that has been penetrated by a burrowing organism, probably a beetle, to produce a *Taenidium* trace. Scale = 1 cm.

Ovoid calies occur either singly or in groups of 5 to 10 irregular, potato-shaped cavities connected by broad horizontal tunnels, protruding above a cemented bedding plane (Fig. 12). Tunnels are ~ 2.5 cm wide and are plano-convex in cross section, with the planar surface as the floor of the tunnel. Calie volumes range from 1 to 30 cc, and they are either: (1) filled with structureless sand, (2) filled with a randomly bioturbated fabric (Fig. 18A), or (3) empty (Fig. 13B). The fragile calie walls are less than 1 mm thick and often incomplete, resembling calcified tissue paper (Fig. 13A). The walls of the interconnecting tunnels are of similar construction. Some ovoid calies have lost the thin external wall completely. The specimens retain their ovoid shape, defined by a complex interlocking mass of small, flattened calcite lined tubes (Fig. 13C). Some ovoid calie and tunnel-network termitaria specimens have been penetrated by *Taenidium* (Fig. 13D).

Tunnel complexes (Fig. 14A) comprise masses of flattened, calcite-lined tunnels, which radiate from a central core, forming a fragile stellate termitarium. Field observations of some specimens show a vertical burrow connecting these structures to the surface. The tunnel systems are clearly made by a similar mechanism to that of the ovoid calies. The tunnels are much smaller in these specimens, about 1 mm high and about 3 mm wide. The walls of the tunnels also are paper thin and calcified. The ovoid calies and the tunnel complexes are both interpreted to be the domichnia of termites (Bown, 1982; Bown and Laza, 1990; Genise and Bown, 1994; Hasiotis and Demko, 1996).

Although termitaria are numerous, the most common trace fossils in the eolianite facies are meniscate burrows and rhizocretions. The meniscate burrows are smooth walled, about 8 mm in diameter, and occur individually and as groups of cross-cutting clusters (Fig. 14B). The meniscate of the infill are clearly defined by their darker

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| Los Angeles gets its water from (a) The Ocean, (b) Mexico, (c) Sierra Nevada, (d) Las Vegas | <input type="checkbox"/> |
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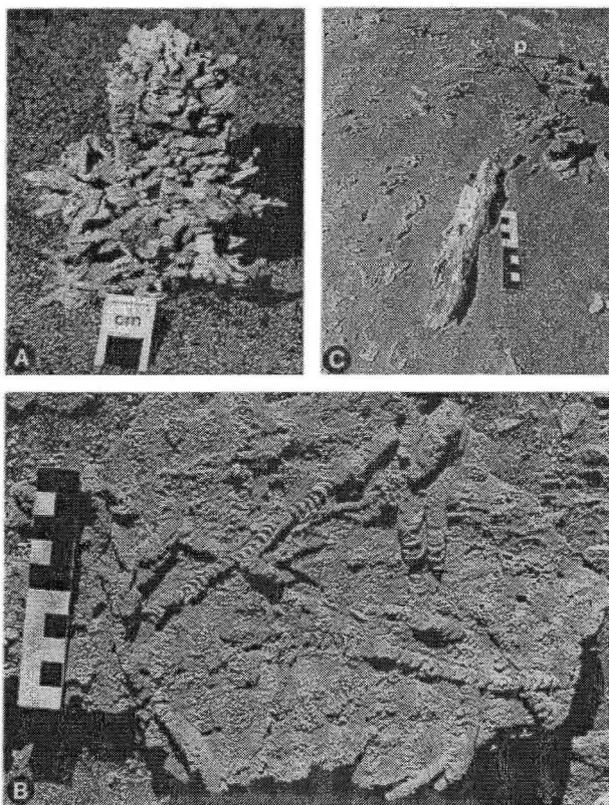


FIGURE 14—Trace fossils of the Khommabes Carbonate Member. (A) Vertically disposed *Termitichnus* tunnel complexes comprising a stellate arrangement of interconnecting calcite-lined tunnels that radiate away from a central vertical axis. (B) *Taenidium* (with meniscate fill) and *Digitichnus* (with walls intact) on a slip face bedding surface of the eolianite facies at Khommabes. Scale in cm. (C) Scattered *Phragmites* reed stem casts (p), preserved in upright growth position and near horizontal rhizcretions (r) identical to those of *Acanthosicyos horrida* (the !Nara plant) that have weathered out of the arenitic carbonate facies. Scale in cm.

color and coarser texture. The burrows are straight to slightly sinuous and unbranched, and appear to be mostly subhorizontal, looping and twisting within the sediment, usually along a particular bedding plane. The dip angle of bedding planes is up to 35°, confirming that they are eolian dune slip faces. Many of the apparent internally structureless burrows display meniscate after the wall has been removed and the wind has etched the infill. This demonstrates that the smooth walls conceal an inner meniscate structure. Thus, we have assigned these two burrow variants to the ichnospecies *Taenidium serpentium*. They occur on the cemented planar cross beds of the eolianite along with short straight unlined and non-meniscate active burrow fills assigned to *Digitichnus* (Ekdale and Picard, 1985). All of these invertebrate burrows are interpreted as having been made by scratch diggers such as the larvae of terrestrial arthropods. Beetles are the most likely candidates. The rhizcretions are vertically to sub-horizontally disposed cylinders of carbonate-cemented sand up to 5 mm in diameter and over 150 mm long. In some cases, the *Termitichnus* tunnels radiate from a vertical

rhizcretion in a similar pattern to those of the extant harvester termite.

Interpretation

This facies is interpreted as the marginal playa facies, overridden at times by migrating dunes. Capillary rise of groundwater up the bedding planes was initially exploited by plant roots, which were, in some cases, later used by termites and beetles as convenient access to their underground nests. The cross-cutting relationships of *Termitichnus* and *Taenidium* suggest that the termite structures were primary and abandoned before being penetrated by *Taenidium*, thus demonstrating a temporal rather than an ecologic succession within this terrestrial ichnofacies (Bromley, 1990). Smith et al. (1993) established the *Termitichnus* ichnofacies as a component of the terrestrial floodplain environment and later Buatois and Mangano (1995) redefined the *Termitichnus* ichnofacies as at the same rank as *Scoyenia* ichnofacies. The Khommabes specimens are accommodated within their definition.

Arenitic Carbonate Facies

Description

The arenitic carbonates of Khommabes are light brown (10YR7/B), unlike the light reddish brown Zebra Pan dolomite. They are characterized by an abundance of calcified *Phragmites* stem casts, preserved in upright growth position, and also by nearly horizontal rhizcretions identical to those of *Acanthosicyos horrida*, the !Nara plant (Fig. 14C). The reed-stem casts are mostly preserved in lengths of less than 0.25 m and in clumps reflective of the life habit of modern reeds. Ward (1984) identified several molluscs in this facies. The rock is burrowed and the bioturbation textures are accentuated by friable red sand that has infiltrated down from the overlying Sossus Sand Formation. Mammalian bones tentatively identified as *Oryx gazella* were recovered from this facies at Khommabes.

Interpretation

The abundance of upright reed casts is an indication that the arenitic carbonate was deposited in a marginal lacustrine environment. The arenite originated from wind-blown sand that saltated into the shallow water and settled on the lake bottom. Seasonal drying caused a gradual lowering of the water level, followed by a short period of subaerial exposure of the marginal lake bed. During the drying-up period, calcite was precipitated around the submerged bases of reed stems and later, as the water level dropped, within the interstitial spaces of the sand grains on the lake floor. The algal encrustation and the length of the reed stems indicates the depth of the standing water at the margins was about 0.25 m. Toppled and broken stem casts suggest that several seasons of reed bed growth are preserved at this site.

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| Northern Namibia occupies which river basin (a) Fish River, (b) Cunene, (c) Orange , (e) Limpopo | <input type="checkbox"/> |
| Humid Tropical soils are (a) shallow, (b) calcium rich, (c) both or (d) neither | <input type="checkbox"/> |
| Jakobshaven Glacier is located (a) Antarctica, (b) Greenland, (c) Iceland, (d) Russia , (e) Canada | <input type="checkbox"/> |
| Which soils are found in the Arid Tropics (a) Oxisols, (b) Mollisols, (c) Gelisols, (d) Ultisols | <input type="checkbox"/> |
| Climatic aridity is caused by (a) high pressure cells, (b) convergence, (c) neither, (e) both | <input type="checkbox"/> |
| Los Angeles gets its water from (a) The Ocean, (b) Mexico , (c) Sierra Nevada, (d) Las Vegas | <input type="checkbox"/> |
| Which is the shorter wavelength region (a) thermal, (b) near IR, (c) UV (d) visible | <input type="checkbox"/> |
| Which of these is not a polar orbiter a) Landsat b) Meteosat c) Spot d) MODIS e) Ikonos | <input type="checkbox"/> |
| Which is the biggest global fresh water store (a) rivers, (b) lakes, (c) groundwater, (d) plants | <input type="checkbox"/> |
| Which country does not have permafrost a) Canada, (b) US, (c) Holland, (d) China, (e) Russia | <input type="checkbox"/> |
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| One polar orbit takes (a) 90 minutes , (b) 24 hours, (c) 12 hours, (d) 60 min to complete | <input type="checkbox"/> |
| What percentage fresh water is not frozen: (a) 10 % , (b) 30% , (c) 50% , (e) 70%, (f) 90% | <input type="checkbox"/> |
| The largest cause of Amazon deforestation is (a) ranching, (b) logging, (c) agriculture, (d) mining | <input type="checkbox"/> |
| Aridsols are (a) rich in iron, (b) calcium, (c) , organics (d) none of these, (e) loess | <input type="checkbox"/> |
| Where is the ITCZ in January (a) equator, (b) northern hemisphere, (c) southern hemisphere | <input type="checkbox"/> |
| Which of these does not reach the ocean (a) Orange, (b)Limpopo, (c) Okavango, (d) Cunene, | <input type="checkbox"/> |
| What is the current annual rate in sea level rise (a) +1, (b) +3, (c) +5, (d) +7, (all in mm) | <input type="checkbox"/> |

Massive Carbonate Facies

Description

This rock is a light gray (10YR7/1), rubbly weathering carbonate that contains scattered detrital medium- to fine-grained, micaceous sand. The paucity of sedimentary structures and the fine grain size indicates that this is the central facies of the playa deposit. Ward reported (1984) that yellow and black varieties of this lithology occur, both of which are relatively silty. Although there are no ichnofossils in this rock, the rubbly texture may indicate that there was some trampling of this sediment by vertebrates before lithification.

Interpretation

The arenitic and massive carbonates were deposited under shallow standing water within an interdune depression. The water depth at the margins as recorded by the algal encrustations on reed stems was 0.25 m. This would have deepened to some 2 m in the center of the depression. Unlike the Zebra Pan playa, the Khommabes-type lakes are closely associated with bedrock highs. They are interpreted as having formed during wetter periods when the perched water table around a bedrock high intersected the surface of wind deflation hollows on the upwind side of the outcrop.

Interpretation of Termite Nests

Published data show that the climate in this part of Africa was wetter during the periods 20,000 to 35,000 BP and 10,000 to 14,000 BP (Teller and Lancaster, 1986). Carbonates from various sources at Khommabes, including calcified root casts of the !Nara plant, "worm casts," and fossil termite nests, have been dated at 21,000–22,000 years BP (Vogel and Visser, 1981). This accords with previous work at the type locality for the Homeb Silts (Smith et al., 1993). Paleoenvironmental reconstruction of that deposit showed that the climate was much wetter, and that the Kuiseb Valley was much wider at that time. It also indicated that the Khommabes Pan sediments represent a lateral continuation of the Kuiseb floodplain. Invertebrate and vertebrate fossils collected from the Homeb Silts indicate a Late Pleistocene age (Marker and Muller, 1978; Ward, 1987; Callum Ross, pers. comm. 1992; Smith et al., 1993).

The *Termitichnus* tunnel complexes were described by Seely and Mitchell (1986) as similar to modern termitaria made by *Hodotermes mossambicus*, the harvester termite. Modern nests with a similar architecture can be observed at the Khommabes site within the root zones of small vegetated coppice dunes. Their tunnel passageways are half moon-shaped in cross-section and are preserved by a millimeter-thick lining of clay that was pasted to the walls by the insects. The wall was an organic structure that has been calcified diagenetically. Most families of modern termites use saliva-cemented clay pellets to build their termitaria. The ancient termites constructed their tunnels in the same way, but the linings were smooth and non-pelleted. The ovoid calie structure may have been an opportunistic response by *Hodotermes* to the erratic rainfall cycles in this part of the Namib during the Late Pleistocene. Sim-

ilar calie structures are built by modern termites in semi-arid soils to ensure a more constant humidity control within the nest chambers (Noirot, 1970). The fossil nests at Khommabes are similar to *Termitichnus qatranii* described by Bown (1982) and Genis and Bown (1994) from the Late Eocene-Early Miocene of Egypt. Hasiotis and Demko (1996) describe four types of termite nests from the Upper Jurassic Morrison Formation of the Colorado Plateau that are closely comparable to those from Khommabes. Two types have networks of tunnels intimately associated with rhizoliths and a third has a calcified ovoid calix. The authors conclude that construction of these nests began around living roots and then continued, after death of the woody plant, to completely fill the rhizolith. Modern termites prefer moist sandy substrates (between 5% and 40% soil moisture) in the upper vadose zone or the upper intermediate vadose zone of soil profile (Hasiotis and Demko, 1996). From the distribution of *Termitichnus*, it appears that such conditions prevailed around the Khommabes and Zebra Pan playas between 30 and 50 cm below surface.

At the time when Khommabes and Zebra Pan were oases, there was a fringe of vegetation around the playas, in part evidenced by the *in situ* plant stems and rhizocretions. The plants provided food for a wetter-climate insect fauna with a different set of behaviors and also sustained some of the larger vertebrates that frequented water holes in this savannah-like environment. Ward (1987) documented the occurrence of elephants and oryx; Smith et al. (1993) recorded bovid footprints in the Homeb Silts, and they also collected zebra and other vertebrate bones from the sediments at Homeb.

SUMMARY AND CONCLUSIONS

The sedimentology and ichnology of two fossil oasis deposits in the central Namib area are used to reconstruct the paleoenvironments. Figure 15 depicts the Zebra Pan deposit as an end-point playa, fed by a channel flowing into the playa from the east, but with no exit. The inset boxes show the different facies and trace fossil associations. Figure 15A illustrates the channel facies where the channel cross cut earlier playa deposits and re-deposited large clasts in a matrix-supported conglomerate. The channelized flow cut into the main playa deposit of microlaminated carbonate before dumping numerous rip-up clasts as a matrix-supported, conglomeratic lag. With renewed influx of sediment-laden floodwater into the playa depression, a new layer of silty sand was deposited over the lake floor. This was followed by a prolonged period of drying, when only millimeter-thick couplets of carbonate were deposited in the central lake. The shallow waters around the margins were soon colonized by reeds, which survived long enough to grow to maturity and become encrusted with microbially precipitated calcium carbonate. With progressive drying, the reed beds died off and newly exposed lake deposits became colonized by terrestrial infauna. The burrows and galleries that are preserved are dominated by *Taenidium*, which is attributed to burrowing by termites and beetles (Fig. 15B). The Zebra Pan deposit was laid down under conditions similar to those prevailing at Sossus Vlei in the modern Namib Sand Sea.

In contrast to the Zebra Pan succession, which records

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| Which of these is not a polar orbiter a) Landsat b) Meteosat c) Spot d) MODIS e) Ikonos | <input type="checkbox"/> |
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| Which country does not have permafrost a) Canada, (b) US, (c) Holland, (d) China, (e) Russia | <input type="checkbox"/> |
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| Aridsols are (a) rich in iron, (b) calcium, (c), organics (d) none of these, (e) loess | <input type="checkbox"/> |
| The largest cause of Amazon deforestation is (a) ranching, (b) logging, (c) agriculture, (d) mining | <input type="checkbox"/> |
| Where is the ITCZ in January (a) equator, (b) northern hemisphere, (c) southern hemisphere | <input type="checkbox"/> |
| Name 4 countries in the Sahel Region _____ | <input type="checkbox"/> |
| What percentage fresh water is not frozen: (a) 10%, (b) 30%, (c) 50%, (e) 70%, (f) 90% | <input type="checkbox"/> |

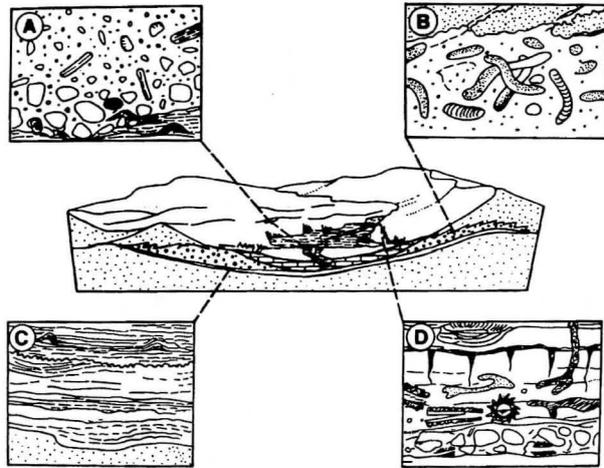


FIGURE 15—Schematic block diagram of the lithofacies and trace fossil assemblages in Zebra Pan-type endpoint paleo-playas of the Central Namib region. (A) Channel-fill conglomerate with carbonate mud clasts. (B) Arenitic dolomite with *Taenidium* and *Digitichnus* burrows. (C) Microlaminated carbonate with isolated algal stromatolites. (D) Massive carbonate with desiccation cracks, unlined *Planolites* burrows, microbially encrusted reed stems, and footprints.

sporadic flash floods followed by fairly rapid drying, the Khommabes deposit appears to have accumulated in a setting that had a more reliable water supply (Fig. 16); evidence for complete drying out is scant. The Khommabes depression was initially formed by wind deflation upwind of a bedrock outcrop. That outcrop also raised the water table to intersect the base of the depression. Again, reed casts with microbial encrustations (Fig. 16B) indicate standing water for extended periods, more likely years than months. A general lack of desiccation features support this interpretation. It also accords well with the climatic information from other published sources, which show that the Late Pleistocene was wetter than today's hyperarid conditions.

Fossil footprints at both Zebra Pan and Khommabes sites (Fig. 16C) illustrate that large vertebrates frequently visited these vegetated oases. The presence of termites is not surprising, as the modern hyperarid desert supports a large and varied animal community that is specially adapted to survive in this harsh environment. In the Late Pleistocene pluvial phases, termites apparently preferred the sandy oasis margins, as their nests are found in the eolianite facies (Fig. 16A). The fossil !Nara rootlets and the other rhizcretions indicate that there was more abundant plant growth than today. Similar deposits at Rooi Lepel near Oranjemund in southern Namibia also contain many termitaria and rhizcretions as well as stratified deposit of egg shells of an extinct giant ostrich (*Diamantornis wardi*), which have been dated as Lower Miocene (Senut et al., 1994).

Figure 17 illustrates the sequence of events that created the Lower Tertiary Zebra Pan deposits. The ultimate control over the stratigraphic distribution of all the ancient playa deposits in this part of the Namib was climate. The climate rapidly changed from arid to relatively wet desert conditions and gradually back to arid again. With in-

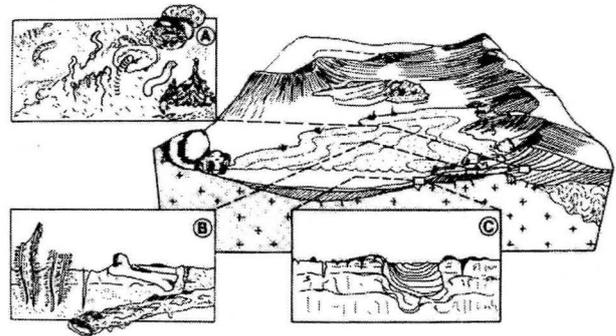


FIGURE 16—Block diagram of lithofacies and trace fossil assemblages of Khommabesh-type paleo-playas in the Central Namib region. (A) Eolianite facies with calcified dune slipfaces that have preserved ovoid and vertical *Termitichnus* nest structures, some of which have been penetrated by *Taenidium* and *Digitichnus* burrows. (B) Arenitic Carbonate facies with *in situ* calcified *Phragmites* reed stems and !Nara-type rhizcretions. (C) Massive Carbonate facies with desiccation cracks and large vertebrate trackways.

creased rainfall, the rivers became less ephemeral but still subject to seasonal floods. Standing water bodies formed at river end-points and wherever the groundwater table intersected the land surface. The earliest wet phase was characterized by a flood occurring every season and by the water slowly drying up. As the climate became drier, the seasonal flows waned and the earlier laminated carbonate deposits were incised by channels created by flash floods.

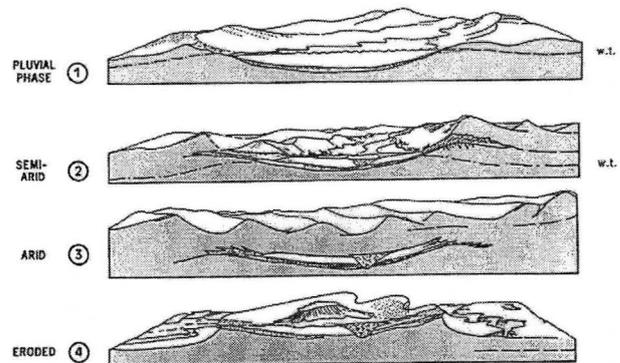


FIGURE 17—Four stages in the generation of fossil oasis deposits in the Central Namib. (1) A pluvial phase causes incision and seasonal flooding of river channels in the interdune areas and the formation of perennial ponds at their endpoints. Elevated water table around bedrock highs also creates surface ponds in the interdunes that are not associated with river channels. Microlaminated carbonates accumulate on the floor of the playa, reflecting seasonal fluctuations in algal productivity. (2) As rainfall diminishes, the dunes become mobile and migrate into the pond margins, becoming part of the playa environment and forming the arenitic carbonate facies. Arid zone vegetation flourishes around the margins and provides a habitat for beetles, ants, and termites. The center of the pond remained flooded for much of the year, accumulating massive carbonate that was periodically exposed to desiccation. (3) With reversion to arid conditions again, the water tables dropped and the playas were abandoned, thus allowing the surrounding dunes to migrate over the interdune areas and bury the already partially consolidated carbonate muds. (4) Recent down-wasting has exhumed and topographically inverted some of the paleo-playas with very little erosion of the limestone deposits.

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| Which of these does not reach the ocean (a) Orange, (b)Limpopo, (c) Okavango, (d) Cunene, | <input type="checkbox"/> |
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| What percentage fresh water is not frozen: (a) 10 % , (b) 30% , (c) 50% , (e) 70%, (f) 90% | <input type="checkbox"/> |
| The largest cause of Amazon deforestation is (a) ranching, (b) logging, (c) agriculture, (d) mining | <input type="checkbox"/> |

When the flows dried up completely, the desert sands buried the older fluvial channels and the dry playas. Subsequent uplift and erosion to the present land surface has exhumed the old playa and its channel, but the remainder of the linear channel deposit that was not cemented by carbonate has been removed completely.

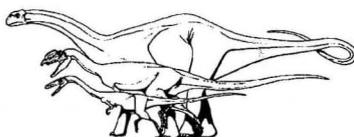
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| Los Angeles gets its water from (a) The Ocean, (b) Mexico , (c) Sierra Nevada, (d) Las Vegas | <input type="checkbox"/> |
| Which is the shorter wavelength region (a) thermal, (b) near IR, (c) UV (d) visible | <input type="checkbox"/> |
| Which of these is not a polar orbiter a) Landsat b) Meteosat c) Spot d) MODIS e) Ikonos | <input type="checkbox"/> |
| Which is the biggest global fresh water store (a) rivers, (b) lakes, (c) groundwater, (d) plants | <input type="checkbox"/> |
| Which country does not have permafrost a) Canada, (b) US, (c) Holland, (d) China, (e) Russia | <input type="checkbox"/> |
| Name 4 countries in the Sahel Region _____ | <input type="checkbox"/> |
| Which one has the lowest spatial resolution (a) Landsat, (b) Ikonos, (c) Spot, (d) MODIS | <input type="checkbox"/> |
| Sea level rise is indirectly caused by melting of (a) glaciers, (b) icecaps, (c) permafrost | <input type="checkbox"/> |
| One polar orbit takes (a) 90 minutes , (b) 24 hours, (c) 12 hours, (d) 60 min to complete | <input type="checkbox"/> |
| What percentage fresh water is not frozen: (a) 10 % , (b) 30% , (c) 50% , (e) 70%, (f) 90% | <input type="checkbox"/> |
| The largest cause of Amazon deforestation is (a) ranching, (b) logging, (c) agriculture, (d) mining | <input type="checkbox"/> |
| Aridsols are (a) rich in iron, (b) calcium, (c) , organics (d) none of these, (e) loess | <input type="checkbox"/> |
| Where is the ITCZ in January (a) equator, (b) northern hemisphere, (c) southern hemisphere | <input type="checkbox"/> |
| Which of these does not reach the ocean (a) Orange, (b)Limpopo, (c) Okavango, (d) Cunene, | <input type="checkbox"/> |
| What is the current annual rate in sea level rise (a) +1, (b) +3, (c) +5, (d) +7, (all in mm) | <input type="checkbox"/> |