Inqua Field Trip Guidebook
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Cenozoic Landforms and Deposits of the western Kalahari and central Namib Desert, Namibia

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Summary

The excursion provides an introduction to landforms and Cenozoic deposits of the western Kalahari and central Namib Desert areas of Namibia. The trip concentrates on aeolian and fluvial landforms and sediments, but includes stops at other important geomorphic features of the area, including the Great Escarpment and the inselbergs and gypsum accumulations of the central Namib plains. The goal of the field excursion is to showcase both classic work and recent research on examples of the major geomorphic features of these areas and to assess their contributions to understanding the geomorphic and climatic evolution of this region during the Cenozoic.

The field trip visits the two major aeolian geomorphic systems of southern Africa: the Kalahari dunes and the Namib Sand Sea. Evidence for past climatic regimes and periods of dune formation are highlighted in the Kalahari stops, whereas the Namib Sand Sea stops include modern aeolian landforms as well as Tertiary aeolian sandstones

that underlie much of the modern sand sea and provide evidence for Miocene - Pliocene aridity in this area. In addition to aeolian systems, the field trip visits classic outcrops of late Cenozoic fluvial deposits in the Kuiseb Valley as well as Tertiary and late Pleistocene pan deposits in the central Namib.

The itinerary begins in Windhoek and traverses the vegetation-stabilized relict linear dunes and dry river valleys of the western Kalahari, before descending the Great Escarpment to the eastern border of the Namib Sand Sea at Sossus Vlei. The trip then follows the eastern edge of the sand sea, with stops at outcrops of Tertiary aeolian sandstone, to the Kuiseb River. The variety of late-Tertiary to Holocene fluvial sediments of the Kusieb Valley are emphasized in the next part of the trip, which ends at Gobabeb on the northern edge of the Namib Sand Sea. Based on Gobabeb, the field trip makes several excursions to view Kuiseb River sediments, sand dunes, and interdune lacustrine sediments, before following the Kuiseb River to the coast at Walvis Bay. En route, there are stops at ventifact sites and gypsum accumulations. The trip briefly examines dunes and marine deposits at the coast, before heading back across the Namib plains with their inselbergs, to ascend the Great Escarpment at its highest and most dramatic part en route to Windhoek. In addition to the formal field trip stops described below, additional informal stops will be made at sites of geologic and general interest. Details of these will be included in a road log to be distributed to participants in the excursion.

In this guidebook section, the stops are grouped by topic and geographic location. A suggested itinerary is as follows:

Day 1: **Kalahari dunes**: Stops 1.1 and 1.2

Day 2: **Great Escarpment**: Stop 2.1; Sesriem Canyon: Stop 5.1 (part)

Day 3: **Sossus Vlei**: Stop 5.1.

Day 4: **Tsondab Sandstone Formation**: Stops 3.1 and 3.2.

Day 4: **Kusieb River**: Stop 4.1 (Carp Cliff);

Gravel Plains: Mirabib Hill (Stop 6.1)

Day 5: **Kuiseb River**: Stops 4.2 (Oswater), 4.3 (Homeb), 4.4 (Gobabeb Gravels)

Day 6: **Namib Sand Sea**: Stops 5.2 (Linear dunes), 5.3 (Khommabes)

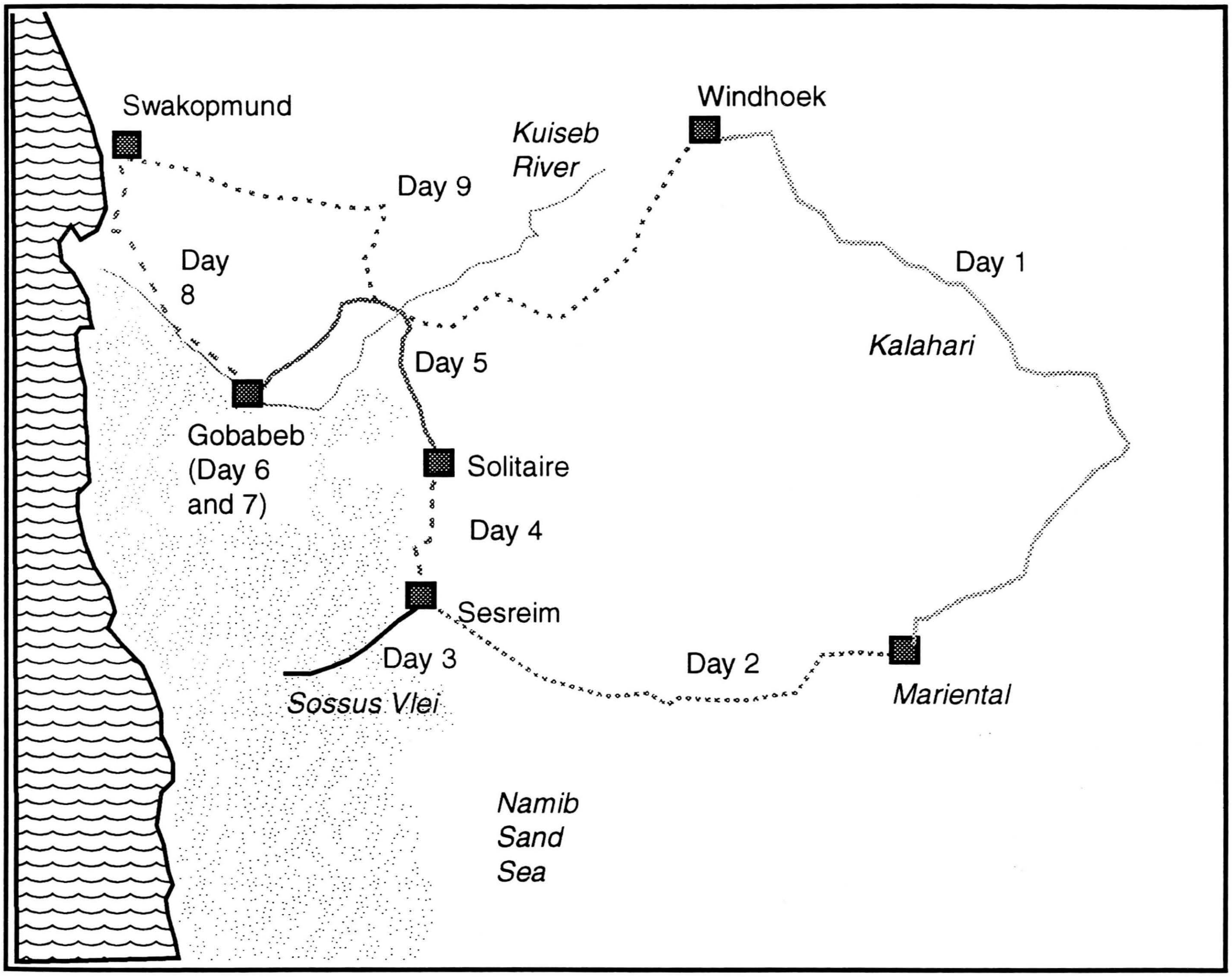
Day 7: **Gravel Plains**: Swartbank (Stop 6.4); Gypsum (Stop 6.2.

Namib Coast: Rooikop Gravels (Stop 7.1)

Day 8: **Gravel Plains**:Vogelfederberg (Stop 6.3).

Great Escarpment: Gamsberg (Stop 2.2)

Fig. 1: Field trip route



Swakopmund
Windhoek
Kuiseb River
Day 9
Day 8
Day 1
Kalahari
Day 5
Gobabeb (Day 6 and 7)
Solitaire
Day 4
Sesreim
Day 3
Day 2
Mariental
Sossus Vlei
Namib Sand Sea

Fig 1

1. LINEAR DUNES OF THE KALAHARI

LOCATION AND ACCESSIBILITY

Linear dunes in the southwestern Kalahari occur in a 100-200 km-wide belt that extends from the highlands of Namibia to the Orange River near Upington. Good areas to see these dunes are on the roads that cross the dune field, especially tbose between Leonardville and Dordabis (C23), and between Leonardville and Stampriet and Gochas and Stampriet (C20). All these roads are suitable for regular sedan cars. Leonardville has a small store, gas station, and hotel. Gas is also available at Stampriet and Gochas.

SIGNIFICANCE

The surface Kalahari Sands extend over an area of 2.5 million sq. km from the Orange River at 29° to 1° N in the western Congo and southern Gabon (Fig. 2) (Thomas and Shaw, 1991). In many places this sand, thought to be at least partly of aeolian origin, forms a gently undulating sand sheet covered by sparse scrub savanna in the southwest to savanna woodland in the north. Extensive systems of dunes, mostly of linear form, occur in the northern and southwestern Kalahari. The dunes can be divided into three groups (Lancaster, 1981; Thomas, 1984; Thomas and Shaw, 1991): an eastern group of degraded linear dunes centered in western Zimbabwe and adjacent areas of Botswana; a northern group of linear ridges vegetated with savanna woodland situated west and north of the Okavango Delta; and a southern group of 2-15 m high narrow straight linear dunes, in the southwestern Kalahari (Fig. 2).

These dune systems provide evidence for the past extent and age of aridity in the interior of southern Africa (Stokes et al., 1998; Stokes et al., 1997b; Thomas et al., 1997). They also provide some information on the nature of past winds and circulation patterns (Lancaster, 1981)

GEOLOGY AND GEOMORPHOLOGY

Stop 1.1: Linear Dunes of the western Kalahari

This stop is located 7 km NW of Leonardville on highway C23. The southern group of Kalahari dunes consists of 2 - 15 m-high straight to slightly sinuous simple and compound partly vegetated linear ridges on NNW-SSE to WNW-ESE alignments. Dune width is commonly 150 - 250 m, with a spacing of 200-450 m (Lancaster, 1988), although some dunes are as much as 2000 m apart. Several varieties of linear dunes have been identified in the region (Bullard et al., 1995; Goudie, 1970; Lancaster, 1988; Thomas, 1986) (Fig. 3). The most widespread are straight sub-parallel or parallel ridges 10-20 m high, with a spacing of 300-400 m and a width of 100-200 m, with rare to scattered Y-junctions that cover much of the central parts of the sand-sea (class 2 dunes of (Bullard et al., 1995); and closely spaced (<300 m apart), low (<10 m high), narrow linear dunes, with common Y-junctions, located southeast of the Molopo River valley (class 3 dunes of Bullard et al., 1995). Discontinuous and reticulate dune patterns occur toward the north and east of the dune field. In addition to the linear dunes, there are small areas of parabolic dunes that may represent a recent reactivation of the system (Eriksson et al., 1989). Vegetation cover on the dune consists of grasses, with scattered trees and shrubs, but the dune crests are commonly unvegetated and active sand movement takes place episodically (Bullard et al., 1997; Wiggs et al., 1995).

The southern dunes are composed of well- to moderately-sorted medium-fine sand with a mean grain size of 170-340 μm. Dune crests tend to be slightly coarser, but better sorted, than adjacent dune flank and interdune areas. Overall, the sand becomes finer and better sorted in a southeasterly direction, parallel to the net direction of sand transport (Lancaster, 1986).

Today, the northern and eastern Kalahari dunes are situated in an area that receives 400 mm or more of rain per year, and are clearly relict forms, By contrast, the southern dunes are episodically active in an area where mean rainfall is 150 -200 mm/yr. Wind energy in current conditions is also too low for widespread aeolian sediment transport in the Kalahari region (Lancaster, 1981; Lancaster, 1988; Stokes et al., 1998; Stokes et al., 1997b). Drier and windier climates are therefore implied for dune building periods in the Kalahari.

Lancaster (1981) identified three paleocirculation patterns based on the pattern of dune alignments: the northern dunes formed when the anticyclonic circulation was much larger in radius; the eastern dunes formed during a period when the South African anticyclone was 2° N of its present position; and the southern dunes formed during a period when the year-round circulation resembled the modern October pattern, with a stronger South Atlantic anticyclone.

STOP 1.2: Age of the dune systems

This stop is located in an area of well-developed linear dunes 34 km NE of Stampriet on highway 42.

Until the recent application of luminescence dating techniques, the age(s) of the Kalahari dune systems was unknown, or inferred by relations to dated lacustrine and fluvial deposits. For example, Lancaster (1989) suggested that periods of dune formation occurred in the southwestern Kalahari prior to 32, 19-17, 10-6 and 4-3 kyr BP.

Luminescence dating and stratigraphic investigations show, however, that the last major period of linear dune development in the southern dune system occurred between 17 and 10 ka and probably involved reworking of sediment deposited in a previous period of dune building from 28 to 23 ka that may represent the initial deposition of sand in this region (Stokes et al., 1997a). Holocene dune activity in the region was localized in extent and occurred at 6 ka and 1 - 2 ka (Thomas et al., 1997).

Parallel studies of dune chronology in the northern and eastern dunes indicate that multiple periods of dune building, each spanning 5 - 20 ka, occurred during the late Pleistocene (Stokes et al., 1998; Stokes et al., 1997a). OSL ages for these periods are 95 - 115, 41 - 46 and 20 - 26 ka. Short-lived periods of aridity were separated by much longer (20 - 40 ka) periods of humid conditions (Stokes et al., 1998). Late Glacial and Holocene aeolian activity was restricted to reworking of the crestal areas of the linear dunes in the area of Hwange National Park in the period 10 - 16 ka.

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Figure Captions

2. Dune systems in the Kalahari (after Thomas 1984 and Lancaster 1981).

3. Dune types in the southwestern Kalahari (after Lancaster 1988 and Bullard et al. 1996)

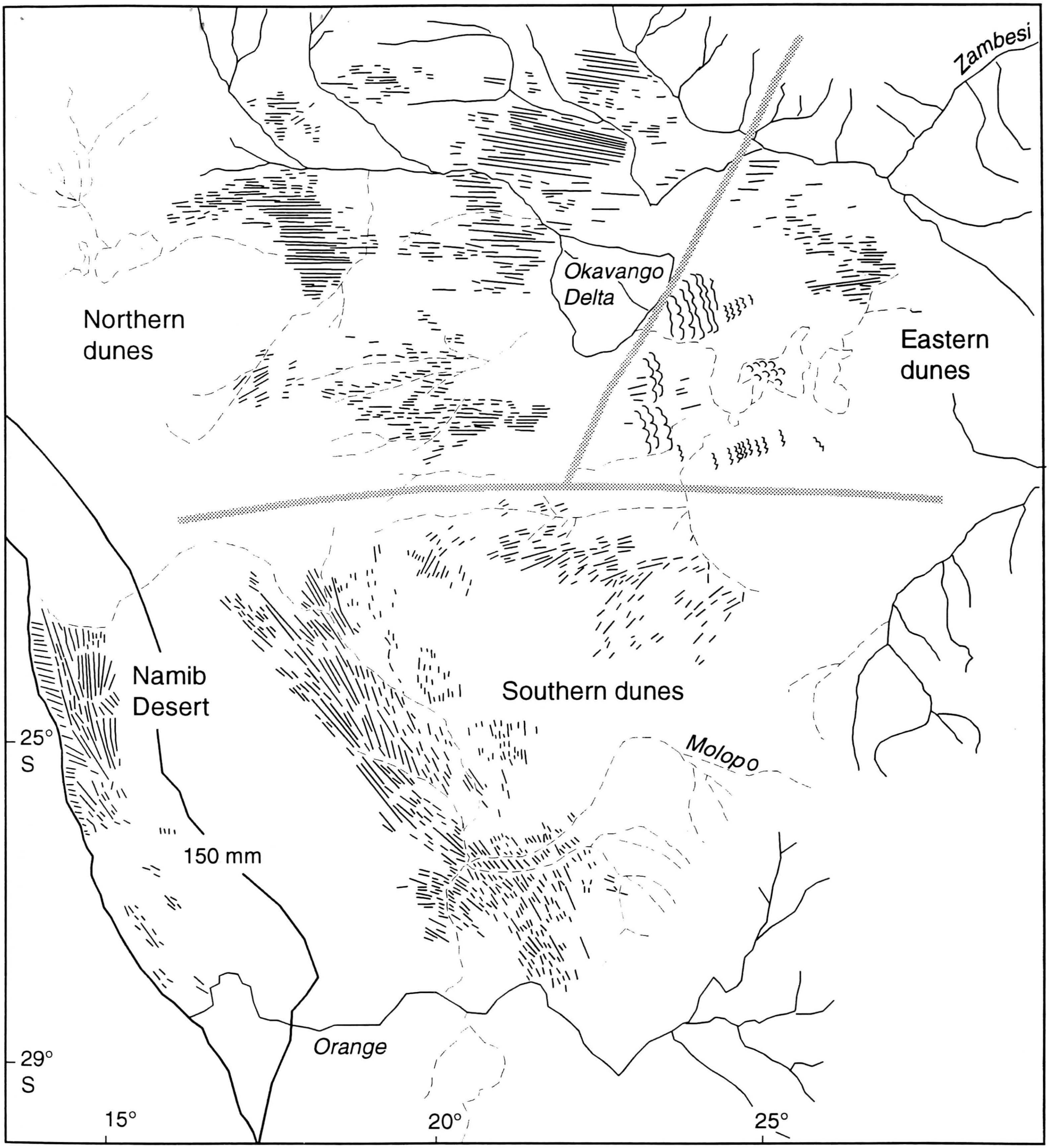
Zambesi
Okavango
Delta
Northern
dunes
Eastern
dunes
Namib
Desert
Southern dunes
Molopo
150 mm
Orange
25°
S
29°
S
15°
20°
25°

Fig 2

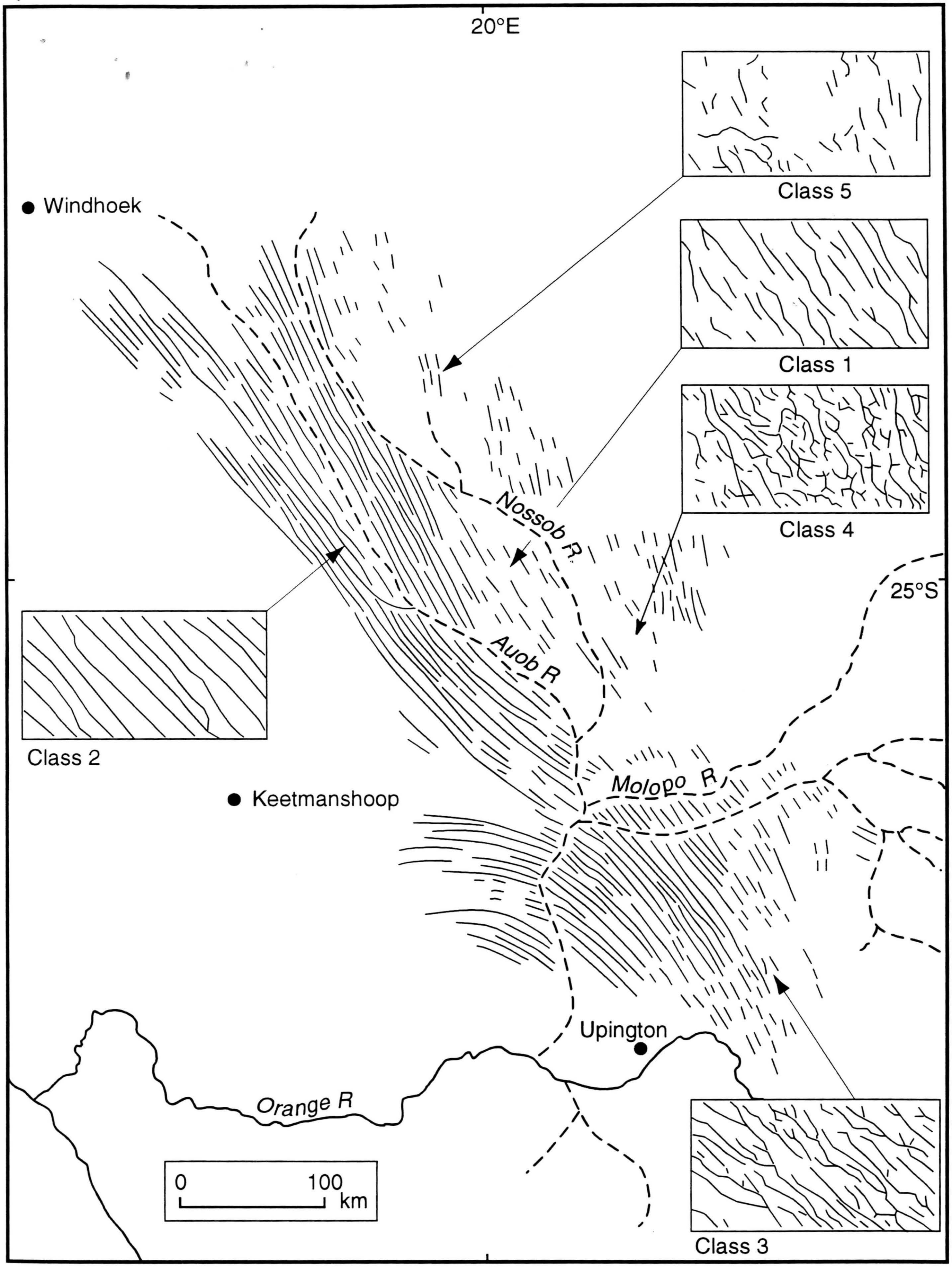
20°E
Windhoek
Class 5
Class 1
Class 4
Nossob R.
25°S
Class 2
Auob R
Keetmanshoop
Molopo R
Upington
Orange R
0
100
km
Class 3

Fig 3

2. THE GREAT ESCARPMENT

LOCATION AND ACCESSIBILITY

The Great Escarpment in Namibia is accessible via several roads that descend from the highlands and plateaus to the Namib Desert. Good locations to see different styles of the escarpment are the Zaris Pass, where flat-lying Paleozoic carbonate rocks overlie Precambrian basement rocks to form the edge of the escarpment: and the Gamsberg Pass, where Jurassic ortho-quartzite caps Proterozoic (Damara) schist. The Zaris Pass is 63 km west of Maltahöhe on highway C14 to Sesriem, and the Gamsberg Pass is 125 km southwest of Windhoek or 289 km east of Walvis Bay on highway C26.

SIGNIFICIANCE

The Great Escarpment separates the coastal lowlands of Southern Africa from the high-elevation interior plateau. Its origins and relations to the tectonic and geomorphic evolution of the sub-continent have been the subject of considerable debate for many years (Marker and Ollier, 1985). Many authors, following King (1962), believed the Great Escarpment to be formed by parallel retreat of slopes following uplift of the subcontinent and initiation of new cycles of erosion after breakup of Gondwana 200 to 95 Ma.

Recently, new tectonic models, evidence from offshore sediments, and advances in dating techniques suggest a more complex pattern for the development of continental margins such as those of southwestern Africa. Southwestern Africa is a mature (>60 Ma) high elevation rifted passive margin, similar to those in eastern Australia and eastern Brazil (Gilchrist and Summerfield, 1991). A typical feature of such margins is a 50 – 300 km wide area of high elevation terrain (1500 - 2000 m in central Namibia) or marginal upwarp which separates the low elevation coastal plain from the continental interior.

The initial rifting and separation of continents is associated with thermal uplift. Following this, cooling and thermal contraction leads to initially to subsidence of the passive margin, reinforced later by sediment loading as denudation of the margin continues. These processes create a flexural bulge landward of a hinge zone (Fig. 4b). As the margin cools and becomes more rigid, the bulge and therefore the axis of maximum uplift migrate inland (Summerfield, 1989). The effects of thermal evolution of the margin are accentuated by the response of denudation to uplift. Higher rates of denudation prevail on the coast-facing side of the upwarp as a result of steep gradients and low base levels, compared to inland, where gradients and rates of denudation are low (Gilchrist and Summerfield, 1990; Summerfield, 1991). Isostatic uplift resulting from rapid denudation and unloading in the zone of the upwarp leads to further uplift of the margin giving rise to a zone of high elevation and high relief 80 - 120 km from the coast (approximately the position of the Great Escarpment in central Namibia).

Data from apatite fission track analysis support such a model for the evolution of the southwestern African continental margin, with a phase of rapid denudation and offshore sediment accumulation occurring during the early Cretaceous during the early stages of the breakup of Gondwana (Brown et al., 1990). Offshore drilling and seismic data in the Kudu section of the Orange sedimentary basin indicate that Cretaceous-age sediments are ~ 3600 m thick, whereas Tertiary deposits are only 600 m (Ward and Corbett, 1990). The data on offfshore sediment thickness and volume suggest that rates of denudation declined from 41 – 82 m Ma^{-1} during the period 152 – 113 Ma to about 7 – 9 m Ma^{-1} from 37 to 1 Ma (Rust and Summerfield, 1990).

Stop 2.1: Zaris Pass

The Great Escarpment at Zaris Pass is typical of the south central part of Namibia. In this area, flat lying sedimentary rocks of the cap the escarpment, which is mainly developed in a variety Precambrian metmorphic and igneous rocks.

Stop 2.2: The Gamsberg

The Gamsberg (2347 m) is the highest point on the Great Escarpment in Namibia. The mountain is capped by a 25 m thickness of flat-lying orthoquartzite of aeolian origin, part of the Etjo Formation (Jurassic). Previous investigators in the region (e.g. (Ward et al., 1983) believed that the Great Escarpment was the result of scarp retreat and pediplanation following breakup of Gondwana some 128 Ma ago.

This model has recently been challenged by data from in-situ cosmogenic isotope studies conducted in the region (Cockburn, 1998). Cockburn (1998) estimated rates of escarpment retreat on the Gamsberg of ~10m Ma^{-1}, using measurements of cosmogenic ^{10}Be and ^{26}Al in quartz. These rates are inconsistent with a uniform rate of escarpment retreat from the coast over the past 130 Ma, but are consistent with data from apatite fission track thermochronology which suggest a rapid retreat of the escarpment soon after rifting, but little change during the Tertiary (Brown et al., 1990).

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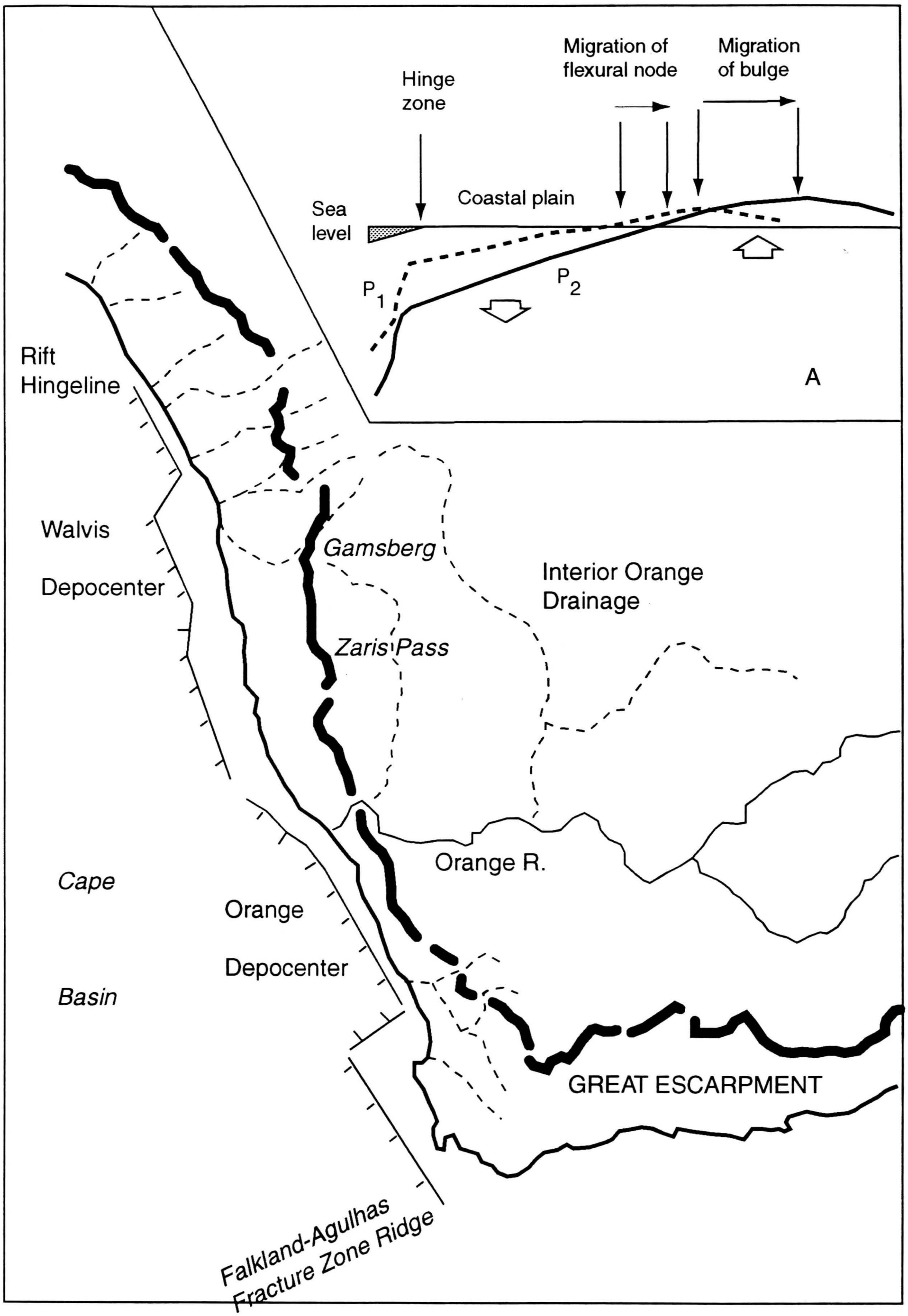
Migration of flexural node
Migration of bulge
Hinge zone
Coastal plain
Sea level
P1
P2
A
Rift Hingeline
Walvis
Depocenter
Gamsberg
Interior Orange Drainage
Zaris Pass
Orange R.
Cape
Basin
Orange
Depocenter
GREAT ESCARPMENT
Falkland-Agulhas Fracture Zone Ridge

Fig 4

3. THE TSONDAB SANDSTONE FORMATION

LOCATION AND ACCESSIBILITY

The Tsondab Sandstone Formation crops out over an area approximately equivalent to the Namib Sand Sea between Lüderitz and just north of the Kuiseb River (Fig. 5) and unconformably overlies Precambrian schist and granites. Over much of its outcrop area, the dunes of the Namib Sand Sea (see below) cover the Tsondab Sandstone and good exposures are limited to the eastern margins of the sand sea. The principal locations are, from south to north: north of the Awasib Mountains, Elim Gullies, on the farm Diep Rivier, the type section at Tsondab Vlei; the Kuiseb Valley in the vicinity of the Carp Cliff and Kamberg, and south of Gobabeb.

With the exception of the exposure on the farm Diep Rivier, all the localities lie within the Namib Naukluft Park and permission from the Ministry of Environment and Tourism, Government of the Republic of Namibia, is required to visit them. Permission from the landowner is required to visit the outcrop at Diep Rivier. Details of access are included with the stop descriptions below.

SIGNIFICANCE

Red brown quartz-rich sandstones that underlie the dunes of the Namib Sand Sea have been recognized by many workers in the region (e.g. Korn and Martin (1955), Besler and Marker, (1979). They were named the Tsondab Sandstone by Ollier (1977) and the Namib Sandstone by Besler and Marker, (1979). The Tsondab Sandstone provides evidence for extensive arid conditions and aeolian deposition of sand during the period 20 to 2 Ma and represents a precursor of the modern Namib Sand Sea. Probable stratigraphic equivalents of the Tsondab Sandstone Formation in the southern Namib are the Fiskus and Rooilepel sandstones (Ward and Corbett, 1990).

GEOLOGY

The Tsondab Sandstone Formation consists of well- to moderately-sorted fine to medium quartz grains with a coating of orange to reddish-brown iron oxides and a patchy carbonate cement (Ward, 1988). It typically exhibits large-scale cross-bedding, with foreset dip directions to the northwest - northeast, indicating accumulation in a wind regime similar to that of today. Thick horizontal to low angle stratification is also observed, and has been interpreted as the deposits of sand sheets (Besler and Marker, 1979). Many beds are affected by intense bioturbation, with common to abundant carbonate-cemented tubules (rhizoliths) and speheroidal structures similar to modern termite chambers (Ward, 1988). The maximum exposed thickness of the Tsondab Sandstone Formation is 90 to

100 m north of the Awasib Mountains and at the type section at Tsondab Vlei, but a 220 m thickness of sandstone was encountered in a water well at Diep Rivier on the eastern edge of the outcrop area (Besler and Marker, 1979).

In the vicinity of the Kuiseb River valley, there are 5 main facies in the Tsondab Sandstone (Ward, 1987): a basal quartz breccia (A), a quartz breccia-conglomerate (B), three quartz arenites (facies C-E), and a carbonate member (facies F). Facies C and D are aeolian in origin and comprise the bulk of the Tsondab Sandstone Formation in the central Namib (Ward, 1987). The uppermost beds of the Tsondab Sandstone Formation (Facies D in the Kuiseb Valley) are characterized by development of polygonal structures, especially where they are overlain by lag gravel of the Karpfenkliff Conglomerate Formation. Earlier workers (e.g. (Watson, 1980) thought that the polygons were the result of desiccation of gypsum-cemented sandstone, but these features are now interpreted to be the products of diagenesis of the sandstone (Ward, 1987), in a manner similar to those that occur in other aeolian sandstones (Kocurek and Hunter, 1986).

Recent detailed studies of sedimentary structures in outcrops at Elim and Diep Rivier (Kocurek et al., in press) indicate that the Tsondab Sandstone Formation consists of dunes that were most likely N-S trending features migrating to the east, with relatively large and slow moving dunes superimposed on their eastern flanks and migrating to the N. The trend and general form of the Tsondab dunes is the same as the modern Namib linear dunes and suggests that similar wind regimes existed during Tsondab time. The extensive nature of plant and animal bioturbation in the studied outcrops suggests, however, that the Tsondab Sandstone Formation accumulated in the presence of much more vegetation and presumably more humid conditions than at the present.

Age of the Tsondab Sandstone Formation

The Cainozoic sediments of the Namib have been divided into 4 groups consisting of a Proto Namib Desert phase (Palaeogene), an Early to Middle Miocene Pluvial phase, a late Middle Miocene pedogenic phase and a Namib Desert phase from the Late Miocene onwards (Ward and Corbett, 1990). In this scheme, the upper Buntfeldschuh Sandstone represents the first evidence of aeolian deposits and a southerly wind regime in the Eocene (Ward, 1987) and the Tsondab Sandstone Formation is assigned a Early-Eocene to Early Miocene age (55 - 20 Ma).

The subsequent discovery of the shells of giant avians throughout the Tsondab Sandstone Formation (Pickford et al., 1995; Senut et al., 1995; Senut et al., 1994) has permitted the development of a biostratigraphy in which these sediments are divided into nine biozones (Table 1), each characterized by a distinct species of giant ostrich-like avian (Pickford and Senut, in press). The age of the eggshells has been determined by correlation of associated small mammal fossils and ranges from 16 - 20 to 2 Ma, with shells of the modern ostrich being of Quaternary age (Pickford and Senut, in press; Pickford et al., 1995). The Tsondab Sandstone Formation therefore accumulated from 20 to 2 Ma and is rather younger than previously suggested by Ward and Corbett (1990). Further, the bulk of the Tsondab Sandstone was deposited prior to the period of fluvial aggradation marked by the Karpfenkliff Conglomerate Formation (Ward, 1987), which has been assigned a early Middle Miocene age, based on lithologic correlation with the Arrisdrif gravels (Ward and Corbett, 1990).

Stop 3.1: Elim Gullies

The Elim Gullies outcrop area is located approximately 10 km north of Sesriem. A 4WD vehicle, plus permission from the Department of Environment and Tourism, are necessary to access this locality. To reach the Elim Gullies from Sesriem, leave Sesriem campground in the NE corner (next to bathroom block). Follow fence (park boundary) for 4.5 km. At 4.5 km, leave fence and follow track west (left) towards Elim Dune (7.1 km). Turn sharp right (soft sand) onto track that leads to NE. Follow this track for 1.8 km to a junction and take the left (west) fork. Continue for a further 3.7 km to a shallow wash. Park on road or in shallow wash and walk 50 m west to outcrop. To visit main Elim Gullies exposures of the Tsondab Sandstone Formation, walk 200 – 300 m NW from south outcrop to gullies. Find a suitable place to descend into the gullies.

Note:

> There is an alternative access to this track from the Elim Dune parking lot via a locked chain. It may be possible to get the key for this from Environment and Tourism. Access to Elim Dune is from Sesriem. Drive 2 km west from Sesriem towards Sossus Vlei and take road to right (unsigned) that leads towards the Elim Dune (approx. 3 km)

The outcrop of Tsondab Sandstone Formation at Elim (Kocurek et al., in press) consists of a series of connected, near vertical walls (Walls A-H) of varying orientations, 2.5-7.5 m high, with a composite length of 76 m (Fig. 6). The outcrop is capped by a deflationary surface littered with calcrete, and overlain by sub-modern, vegetated, aeolian sands. The outcrop can be divided into: (1) a lower series of sets bounded by prominent surface 1, (2) a middle, completely bioturbated zone overlying the surface, and (3) an upper single set bounded by surface 2. Plant and animal bioturbation is prominent throughout the outcrop. In some cases, bioturbation is focused along foresets and surfaces, thereby enhancing these, but in other cases bioturbation has destroyed any primary structure. Avian eggshells reported by Pickford et al. (1995) place the main body of the outcrop in the *Namornis oshanai* zone, with an age of 15-16 Ma, while the capping deflationary surface 2 yielded eggshells from *Struthio daberasensis* of a post-Miocene age.

The lower series of sets consists of two different orientations. Sets with apparent dips to the left on Walls A-B on Figure 2 consist of foresets dipping toward the S to SSW. Sets with apparent dips to the right on Walls B-H consist of foresets dipping toward the NNE to SSE. These sets of differing orientations overlap in Wall B to produce a 'zigzag' arrangement. Sets consist of grainflow strata with less abundant wind-ripple laminae. Scalloped bounding surfaces, dipping E to ESE, occur within the lowest set on Walls C and E, and are probably present elsewhere.

Prominent surface 1 that caps the lower series of has a relief of about 3 m. The bioturbated zone overlying this surface on Wall A is about 0.7 m thick, and the extent of bioturbation extending downward from this zone progressively increases to a maximum on Wall H.

The upper set of compound cross-strata, up to 1.6 m high, is poorly exposed, but foresets generally dip to the ENE to E.

Stop 3.2: Diep Rivier

The outcrop of Tsondab Sandstone at Diep Rivier is located on the farm Diep Rivier, next to the farm buildings. It is reached by the farm and rest camp access road from highway #36 that runs from Maltahöhe to Solitaire. The turn off for the farm road is located 221 km from Maltahöhe (stores, gas stations, hotel, 72 km from Sesriem (lodge, campsite, gas, small store), and 28 km south of Solitaire (gas, small store). The outcrop lies 6 km west of the main road, from which it can easily be seen.

The outcrop at Diep Rivier has two parts (Kocurek et al., in press). The main part of the outcrop is a cliff up to about 90 m high, and trending about N23W. Beginning near the southern terminus of this outcrop and extending southward is a bench that exposes in a horizontal section several hundred meters of cross-strata (Fig. 8). As at Elim, the Diep Rivier outcrop is divided into (1) a lower series of sets capped by prominent surface 1, (2) a bioturbated zone overlying the surface, and (3) an upper series of sets. The caliche-littered deflation surface, surface 2, capping the upper sets occurs only in the southern portion of the cliff, with the outcrop progressively downcut to the north. Similarities in the stratigraphic zones to Elim are in agreement with the biostratigraphy, with the Diep Rivier outcrop yielding the early Miocene *Namornis oshanai* and *Struthio daberasensis occurring* on deflationary surface 2 (Pickford et al. 1995).

The lower series of sets along the Diep Rivier cliff consists of at least three large sets and a complicated array of small sets (Fig. 8). The lower large set, up to 20 m thick, shows cross-strata that exhibit a regular progression in foreset orientation, dipping toward the NE at the southern end of the and to the SE at the northern extent of the set. The two sets, each averaging about 20 m thick, in the northern portion of the traverse consist of a range of foresets dipping S65E to E. Both sets yield southward to tangential foresets marked by intense bioturbation at the lowest elevations of the sets. A bioturbated horizon about 1.5 m thick occurs between the two sets, and appears to thicken into a prominent 6 m thick bed in the center of outcrop. The central part of the outcrop is complex, with both intense bioturbation and a complicated arrangement of sets. Numerous foreset measurements in this zone showed a range (N25E - S80E) in part coincident with foresets measured in the lower set at the southern end of the traverse (N55E - S52E).

As at Elim, surface 1 bounding the lower sets is not horizontal, but irregularly rises about 20 m northward along the traverse. The surface is overlain by about 1.5 m of intensely bioturbated sand, with the bioturbation extending down from the surface into the underlying sets.

Correlative to the upper set at Elim, at least four sets, ranging in thickness from 10 to 26 m, occur at Diep Rivier. Foreset measurements from the sets at the southern portion of the traverse showed a range of S60E - S85E, but the set at the northern extreme of the traverse showed a dip toward the N25-46E. Stratification consists of mainly grainflow foresets, with lesser amounts of wind-ripple laminae, both of which toe tangentially to horizontal, heavily bioturbated bottomsets up to 1.5 m thick.

Bioturbation at both the Elim and Diep Rivier outcrops can be summarized as (1) intense zones overlying the prominent bounding surfaces, (2) extending from the surfaces into the underlying sets, (3) intense zones that interbed with foresets, and (4) pervasive throughout the cross-strata. The bioturbation is very varied in size and structure, with clear examples of carbonate-cemented roots and termite nests.

Table 1: Biostratigraphy of the Tsondab Sandstone Formation (after Pickford et al, in press)

Biozone	**Species**	**Associated mammals**	**Deduced Age**
6	Struthio camelus	Lepus capensis Oryx gazella	Quaternary
5	Struthio daberasensis	Cryptomys Lepus capensis Bathyergus sp. Petromys sp. Gerbillus sp. Otomys sp.	Post-Miocene
4	Diamantornis laini	Parapedetes namaquensis Giraffidae Ternania sp.	Late Middle Miocene or base of Upper Miocene
	Diamantornis wardi	Parapedetes namaquensis Bathyergoides neotertarius Macroscelidea Gomophotheriidae	Early Middle Miocene
2	Diamantornis corbetti	Parapedetes namaquensis Bathyergoides neotertarius Macroscelidea Gomophotheriidae Paracrytomys	Lower Miocene
1	Namornis oshanai	None	Pre-Miocene or Lower Miocene

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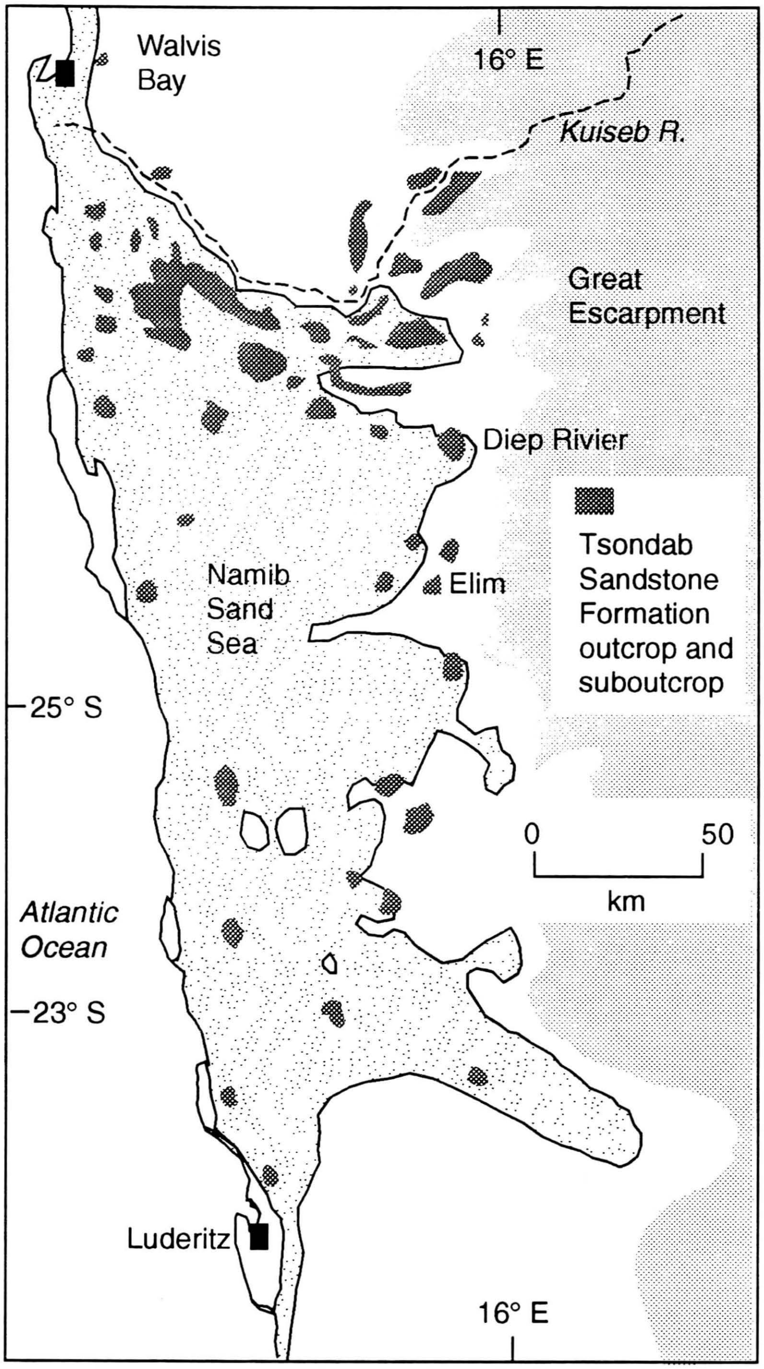
Walvis Bay
16° E
Kuiseb R.
Great Escarpment
Diep Rivier
Tsondab Sandstone Formation outcrop and suboutcrop
Namib Sand Sea
Elim
25° S
0
50
km
Atlantic Ocean
23° S
Luderitz
16° E

Fig 5

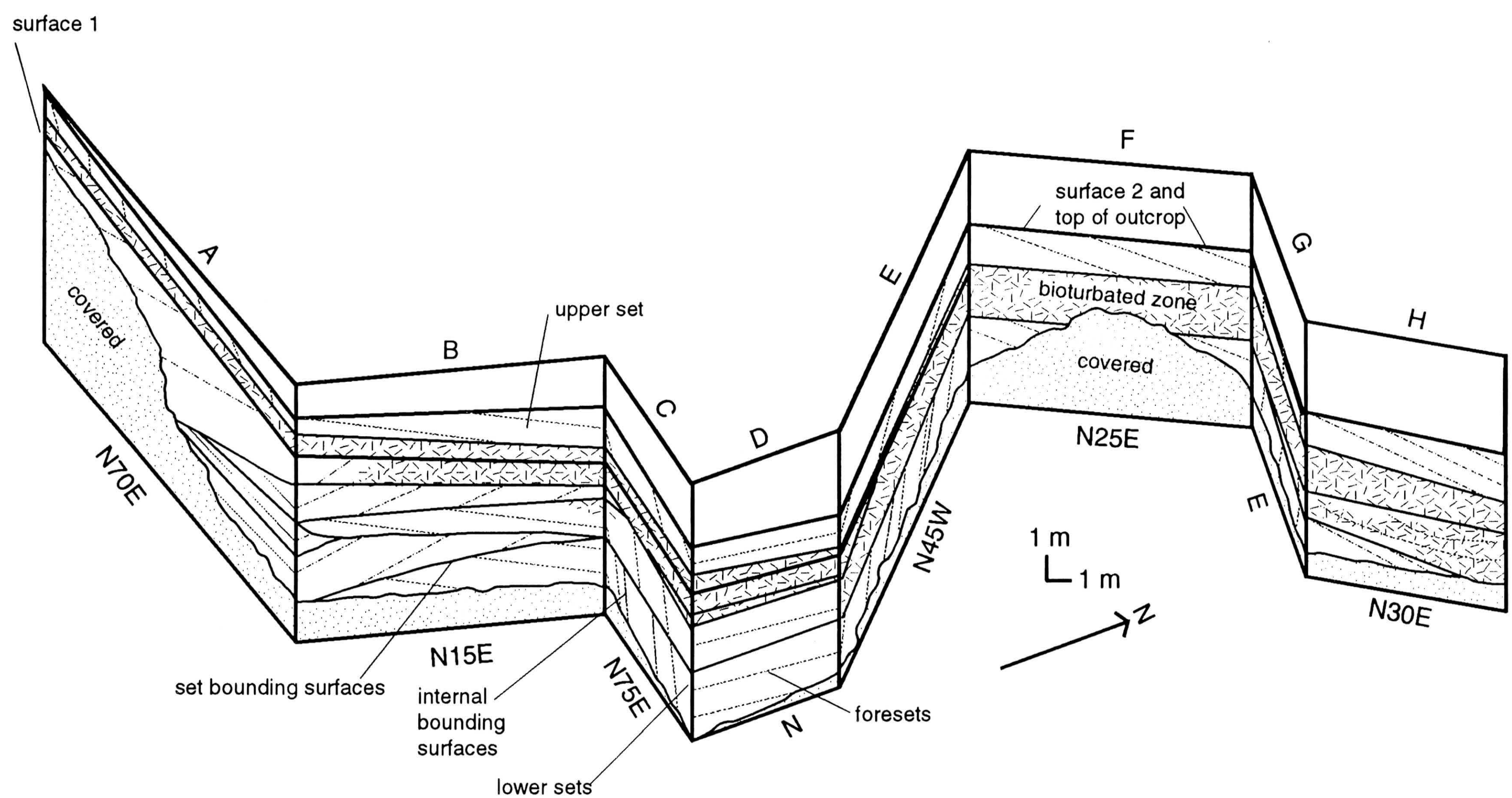
surface 1
A
covered
N70E
B
upper set
N15E
set bounding surfaces
internal
bounding
surfaces
lower sets
C
N75E
D
N
foresets
E
N45W
F
surface 2 and
top of outcrop
bioturbated zone
covered
N25E
G
E
H
N30E
1 m
1 m
N

Fig 2

~~7~~ 9

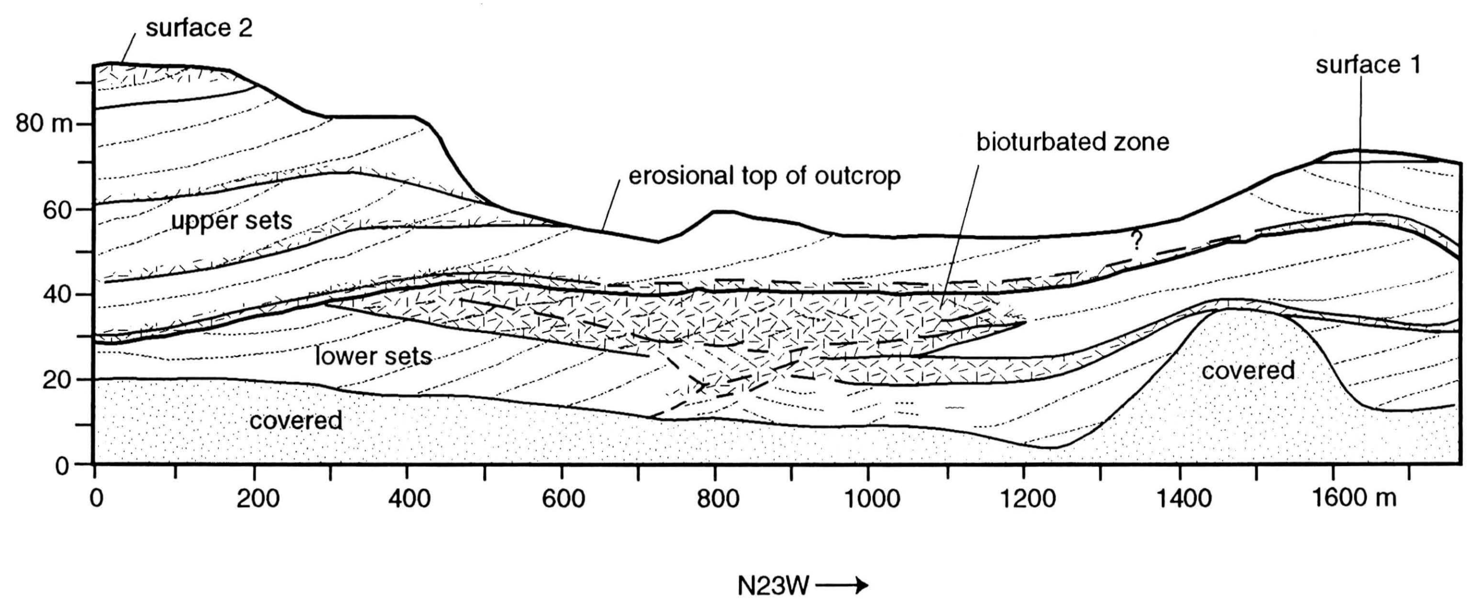
surface 2
surface 1
bioturbated zone
erosional top of outcrop
upper sets
lower sets
covered
covered
80 m
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600 m
N23W

Fig 7

Figure Captions

5. The Tsondab Sandstone Formation - location of outcrops in the central Namib (after Ward, 1988).

6. Section of the outcrop of the Tsondab Sandstone Formation at Elim(from Kocurek et al, in press)

7. Section of the outcrop of the Tsondab Sandstone Formation at Diep Rivier (from Kocurek et al, in press)

4. FLUVIAL DEPOSITS OF THE KUISEB VALLEY

LOCATION AND ACCESSIBILITY

The Kuiseb River (Fig. 8) has a catchment area of 15,500 km^2 and extends for some 420 km from its source near Windhoek to the delta region south of Walvis Bay (Jacobson et al., 1995). Its valley forms the northern margin of the Namib Sand Sea. Outcrops of Cenozoic fluvial deposits are mainly confined to the area west of the Great Escarpment, from the vicinity of the Us Pass road westward to the vicinity of Gobabeb. Easily accessible localities (no 4WD) at which to examine such deposits are at the Kuiseb Canyons overlook just west of the Kuiseb Bridge on the main Maltahöhe-Walvis Bay road and at Homeb in the lower part of the incised reach of the Kuiseb River (Namib Naukluft Park Permit required for both localities). 4WD vehicles and special permission from the Ministry of Environment and Tourism, Government of the Republic of Namibia, are required to visit Oswater and the Gobabeb Gravels localities described below. Directions for each locality are included with the descriptions of the stops.

SIGNIFICANCE

Thick sequences of conglomeratic sediments of fluvial origins have been recognized in many of the major drainages of the central Namib Desert (e.g. Tsauchab, Tsondab, Swakop rivers) (Korn and Martin, 1955). They overlie, in erosional contact, the Tsondab Sandstone Formation or Precambrian bedrock. Fluvial deposits of the Kuiseb River valley have been studied in detail and provide evidence for the changing nature of climatic and tectonic environments in this region during the Cenozoic.

GEOLOGY

Stop 4.1: Carp Cliff

The type section for these conglomerates is at Carp Cliff (23° 20"S, 15° 45' E.), and is described by (Ward, 1987) and illustrated in Fig. 9. This site is reached as follows:

Km 0	Kuiseb Bridge
Km 8	Kuiseb Canyons road. Turn left. Namib Naukluft Park permit required to visit mesas.
Km 12.5	Carp Cliff Mesa. Road junction. Bear right to southwesterly end of mesa. (end of road).
Km 13.5	Park at road end, walk northeast back along road to tree on cliff edge. Descend NE into upper canyon to type section described in Ward (1987).

The Karpfenkliff Conglomerate Formation in the Kuiseb Valley consists of rounded to well rounded carbonate-cemented gravels in a medium sand matrix. Clast lithology is dominated by metaquartzite and vein quartz derived from the Damara Sequence, as well as quartzite of the Jurassic Etjo Formation that caps the Gamsberg. Clast size decreases westwards from boulders and cobbles in proximal areas to pebbles in distal exposures. There is commonly an upward-fining trend in proximal exposures, which are massive to horizontally bedded, with imbricated clasts.

In the Kuiseb Valley, the conglomerate extends from the base of the escarpment where is as much as 60 m thick to about 15° 29'E. West of this point, the Karpfenkliff Conglomerate Formation mainly consists of thin (< 5 m) conglomerates and lag gravels. From 15°10'E at Natab, the gravels continue to the west as exposures in interdune areas, whereas the Kuiseb Valley turns northwards, indicating diversion of the river to the north by invasion of dunes from the south.

According to Ward (1987), the Karpfenkliff Conglomerate Formation was deposited in shallow valleys by braided streams draining the escarpment zone, possibly in wetter climates than exist today. Ward (1987) suggests an Early-Middle Miocene age for these conglomerates, on the basis of correlation with the Arrisdrift Gravel Formation with its well-dated fauna (Ward and Corbett, 1990).

In many localities, the Karpfenkliff Conglomerate Formation is capped by the Kamberg calcrete, a regionally-extensive calcrete of pedogenic origins that also caps the Tsondab Sandstone Formation. The calcrete is highly developed and as much as 5 m thick (Yaalon and Ward, 1982). It is indicative of a long period of landscape stability in the region prior to cutting of the Kuiseb and other major valleys. Ward (1987) assigns the Kamberg calcrete an end-Miocene age.

Stop 4.2: Oswater

To reach this locality, follow these directions from Homeb:

Km 0	Homeb Camp Site. Pass through camping area to no entry sign. Engage 4WD and enter river bed. Drive downstream (right).
Km 8.6	Stop 4.4: Gobabeb Gravel Formation on north bank of river. Stop in river and walk north to outcrop.
Km 10.6	Stop 4.2: Oswater Conglomerate Formation. Stop at granitic rock outcrop on south bank of river. Walk west on south side of river between riparian vegetation and the rock outcrop to reach the goat trail that leads west for 400 m to the Oswater Conglomerate Formation outcrop.

Retrace route to Homeb or continue down river bed to Gobabeb (22 km from Homeb)

The Oswater Conglomerate Formation (Fig. 10) is a suite of cemented gravels that form a prominent terrace between 30 and 70 m above the present level of the Kuiseb River from the base of the escarpment west to Gobabeb (Ward, 1987). The gravels rest unconformably on Precambrian bedrock and represent a major aggradational phase of the Kuiseb River. The thickness of the Oswater conglomerate increases from 5-6 m in proximal areas to 30-40 m in the Kuiseb Canyon and then decreases to a 20 – 30 m exposed thickness downstream from Homeb.

The Oswater conglomerate consists of gravels and intercalated sands, in an sandy matrix and cemented by calcium carbonate. Clast lithology is similar to the Karpfenkliff Conglomerate Formation, with the addition of clasts of the Kamberg calcrete. (Ward, 1987) distinguishes three facies in the Oswater conglomerate: (1) a proximal reach characterized by large boulder-sized clasts of metaquartzite; (2) a mid reach in the Kuiseb canyon, where the conglomerate consists of well-rounded cobbles and small boulders that are both matrix and clast supported. The conglomerates form flat-lying beds intercalated with subordinate arenite beds up to 2 m thick; and (3) a distal reach characterized by clast supported cobble-pebble conglomerate with lenses of quartz arenite (channel fill deposits). There are also wedges of high-angle cross-stratified quartz arenite of probable aeolian origin in some south bank exposures in this reach.

Ward (1987) believed that the Oswater conglomerate was deposited in a confined valley by a braided stream that had a higher competence and a steeper gradient than the modern Kuiseb River and was fed by more abundant seasonal runoff in the Khomas Hochland zone. The wedges of cross-stratified arenite are the first evidence of dunes in this part of the Namib. Ward (1987) suggests a Early to Middle Pleistocene age for the Oswater Conglomerate Formation. Similar conglomerates occur in the valleys of the Tsondab, Swakop, Khan, Omaruru, and Ugab rivers, the major drainages of the Skeleton Coast, and the Engo and Kunene rivers.

Stop 4.3: Homeb Silt Formation

An excellent locality at which to examine the Homeb Silt Formation is the area of the type section just north of Homeb village. To reach this stop from Gobabeb:

Depart Gobabeb and turn right (east) at gate.

Km 3.6	Junction with road to Homeb. Turn right.
Km 16.4	Homeb road. Turn right.
Km 18.4	Junction with Zebra Pan road. Turn right (south)

Km 21.2 — and descend into Kuiseb Valley.

Km 21.2 Stop: 4.3 Homeb Silt Formation. Park on edge of road and walk 100 m east to outcrop.

The Homeb Silt Formation consists of up to 25 m thickness of horizontally-bedded micaceous yellowish brown to grey muddy silts, with interbedded coarse silt and red-brown sand (Fig. 11). There are scattered lenses of locally derived angular quartz and schist gravel. The Homeb silts occur mainly in the area between Gomkaeb and Soutrivier and are preserved in embayments (tributary valleys) in the Damara schist bedrock, at elevations of up to 45 m above the present river level, principally on its north side. In places, the Homeb silts abut the Oswater Conglomerate. A possible downstream equivalent of the Homeb Silts may be the Awa-gamteb muds, poorly exposed adjacent to the present Kuiseb Delta (Ward, 1987).

The sedimentology and stratigraphy of the Homeb silts is described in detail by (Marker and Muller, 1978) and (Ward, 1987). The muddy silt layers are typically massive, whereas coarse silt layers exhibit horizontal and climbing ripple lamination. There are desiccation cracks, small channels, carbonate nodules and pedotubles, and many soft sediment deformation structures throughout this deposit. The Homeb Silts contain shells of the gastropods *Bulinus tropicus, Biomphaleria pfeifferei, Xerocerastus* spp. and *Sculptaria sculptaria* (Marker and Muller, 1978).

The depositional environment and origin of the Homeb Silt Formation have been interpreted in three main ways: (1) sediments deposited behind a dune dam (Goudie, 1972; Rust and Wieneke, 1974); (2) terminal playa sediments (Marker and Muller, 1978; Vogel, 1982); and (3) fine-grained fluvial deposits (Ollier, 1977; Ward, 1987). Sedimentary structures, the absence of physical evidence for dunes blocking the valley, as well as the overall downstream gradient of the silt beds, point to a low-energy fluvial origin for the Homeb Silt Formation.

Radiocarbon dates from calcareous crusts, gastropod shells, and wood fragments contained in the Homeb Silts (Vogel, 1982) range between 23,000 B.P. and 19,000 B.P.

Similar silt deposits also occur in many other rivers of western Namibia (e.g. Swakop, Omaruru, Huab, Hoanib, and lower Hoarusib). Those in the Hoarusib River have radiocarbon ages of 42.6 to 21.4 ka, or rather older than the Homeb Silts (Rust and Vogel, 1988).

Stop 4.4: Gobabeb Gravel Formation

This stop is best combined with a visit to the Oswater Conglomerate Formation locality (see above). Poorly exposed outcrops of the Gobabeb

Gravels can also be examined in the washes south east of Gobabeb

Gravel deposits at elevations ranging from a few meters to about 30 m above the present level of the Kuiseb River have been identified by many workers in the region (e.g. Goudie, 1972; Marker, 1977; Ollier, 1977; Rust and Wieneke, 1980). They were named the Gobabeb Gravel Formation by Ward (1987). The Gobabeb Gravels directly overlie bedrock and the Homeb Silt Formation and extend from base of the escarpment to the delta. Their thickness ranges from 3 m near the Kuiseb Bridge to less than 2 m in the middle course of the river and 5 m near the delta (Ward, 1987). In many areas of the middle reaches of the Kuiseb Valley, gravels of tributary washes grade to the elevation of the Gobabeb Gravel Formation.

The Gobabeb Gravels consist of loosely-cemented well-rounded boulder-cobble to pebble-cobble gravels typical of those in older Kuiseb Valley sediments together with locally derived clasts of schist, dolerite, marble, calcrete, and gypsum set in a sandy matrix (Ward, 1987). Many of the clasts have a distinct iron oxide stain, giving this unit a distinctive brownish-yellow color. The Gobabeb Gravels are uncemented and exhibit weak, vesicular calcrete development in lower reaches of the river. Ward (1987) interprets the Gobabeb Gravel Formation to represent a degradational sequence of deposits laid down as the Kuiseb River incised following deposition of the Homeb Silt.

The age of the Gobabeb Gravel Formation is latest Pleistocene because it overlies the Homeb Silt Formation, with radiocarbon ages of 23,000 to 19,000 B.P. (Vogel, 1982), with carbonate from the "12 m terrace" providing a date of 9,600 B.P. (Vogel, 1982).

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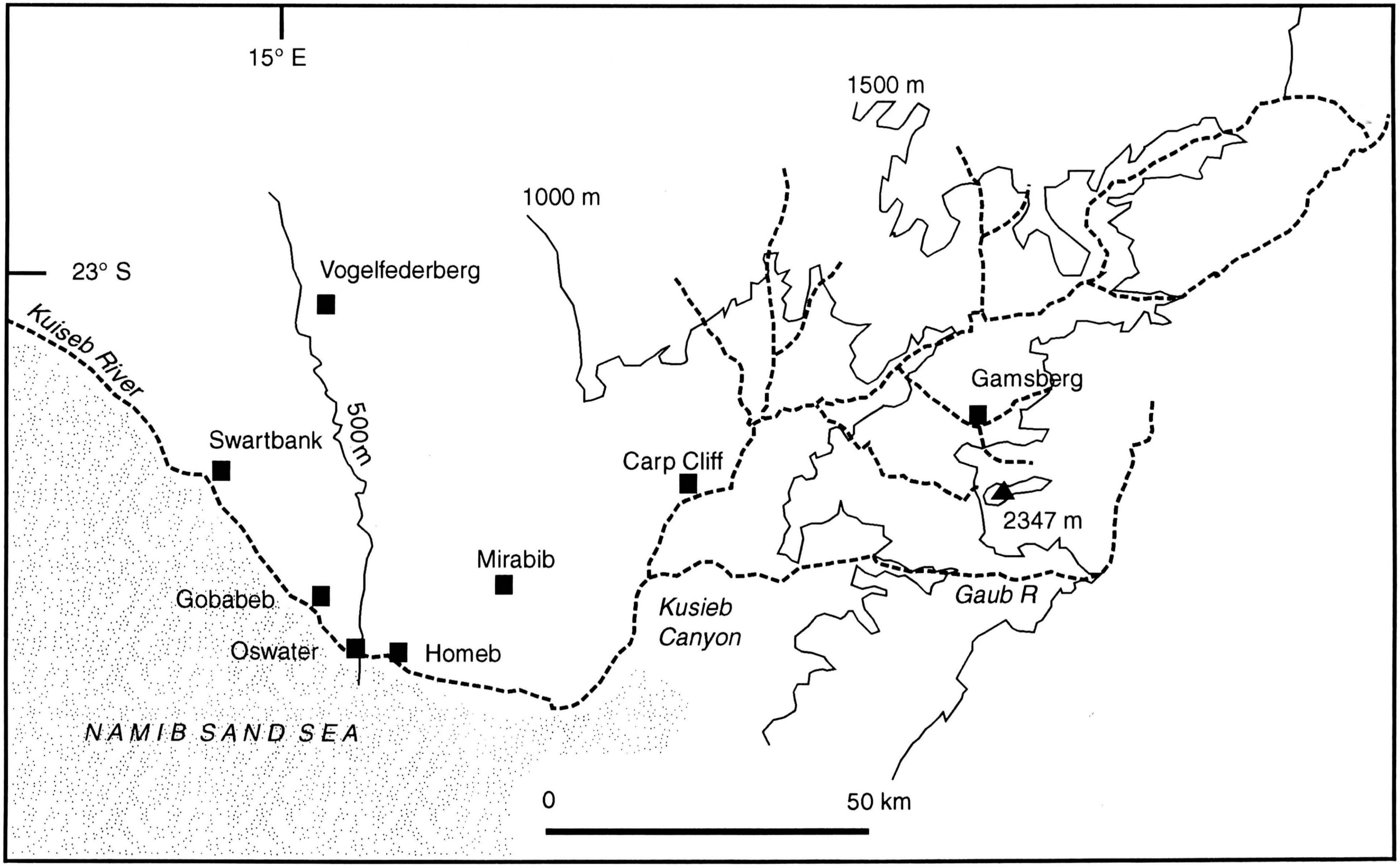

15° E
23° S
1500 m
1000 m
Vogelfederberg
Kuiseb River
500m
Swartbank
Carp Cliff
Gamsberg
2347 m
Mirabib
Gobabeb
Oswater
Homeb
Kusieb
Canyon
Gaub R
NAMIB SAND SEA
0
50 km

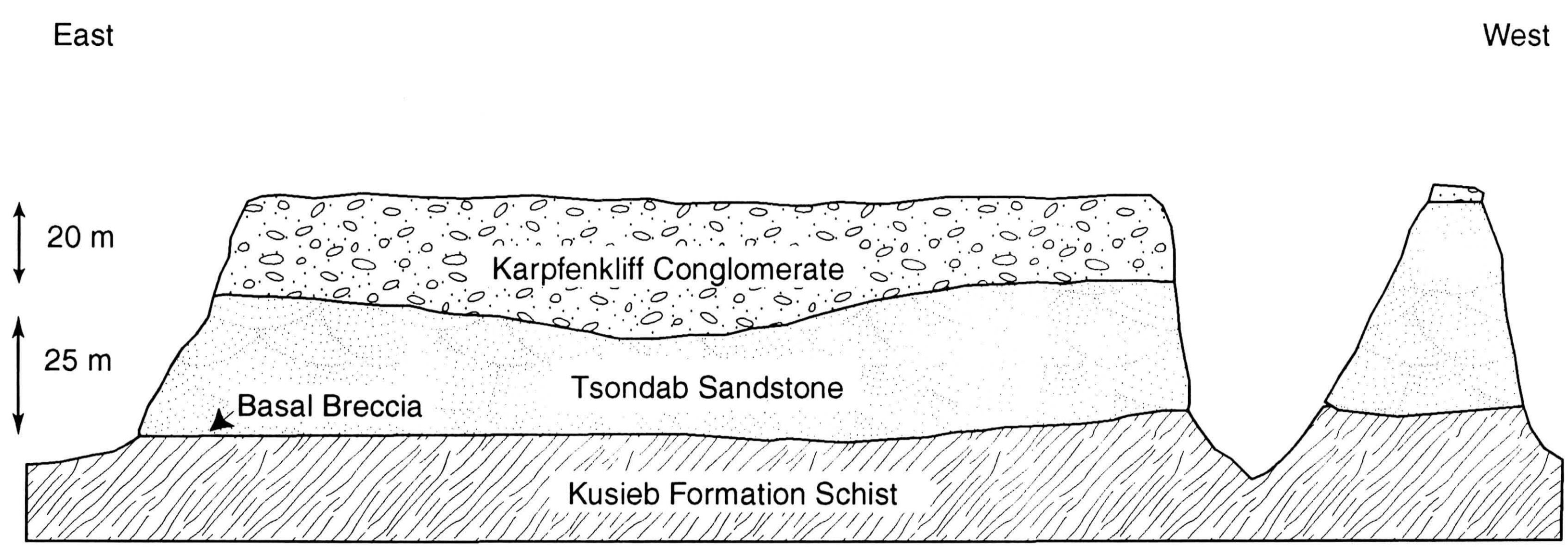
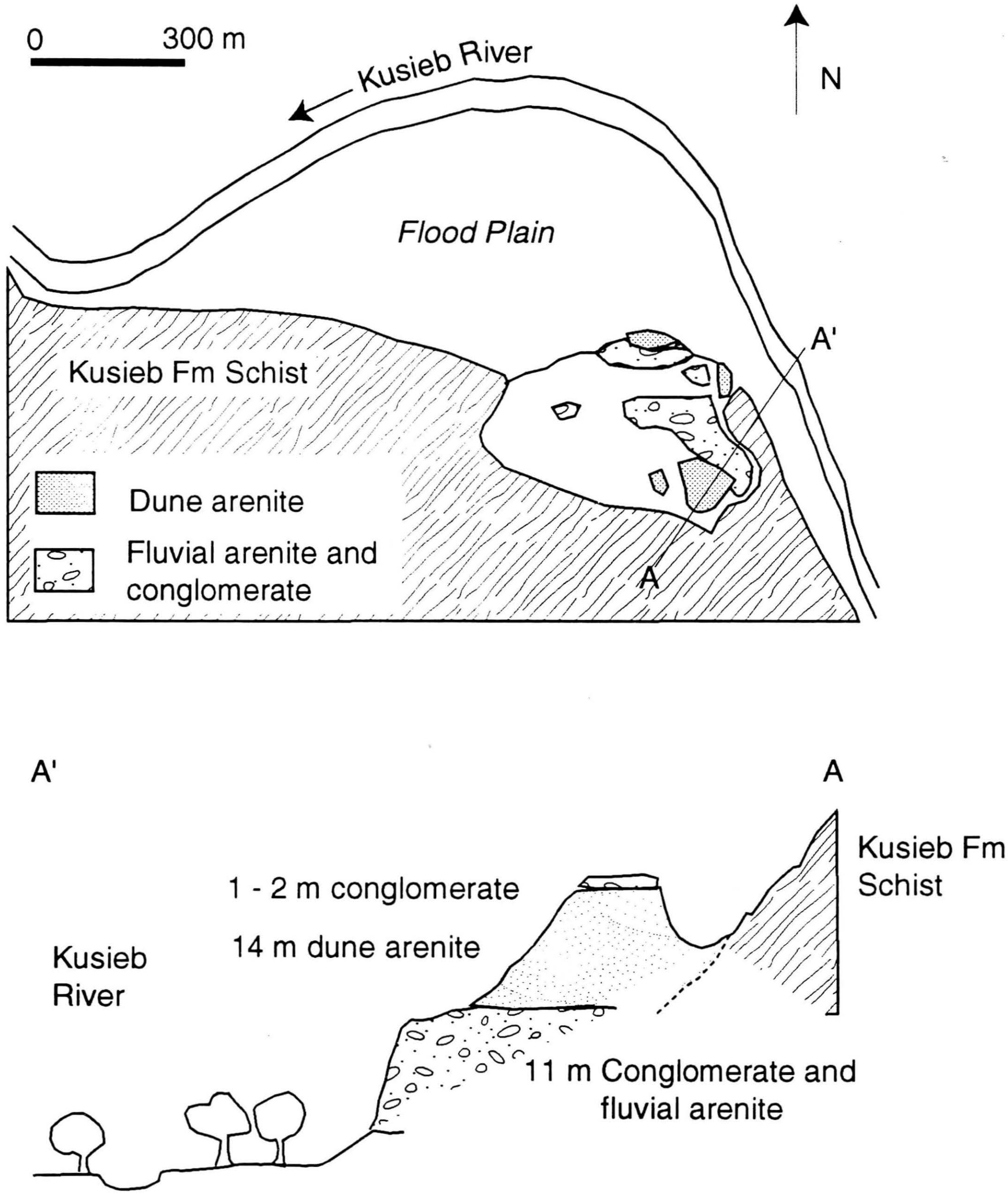

East
West
20 m
25 m
Karpfenkliff Conglomerate
Tsondab Sandstone
Basal Breccia
Kusieb Formation Schist

Fig 9

Fig 10



0
300 m
Kusieb River
N
Flood Plain
A'
Kusieb Fm Schist
Dune arenite
Fluvial arenite and
conglomerate
A
A'
A
Kusieb Fm
Schist
1 - 2 m conglomerate
14 m dune arenite
Kusieb
River
11 m Conglomerate and
fluvial arenite

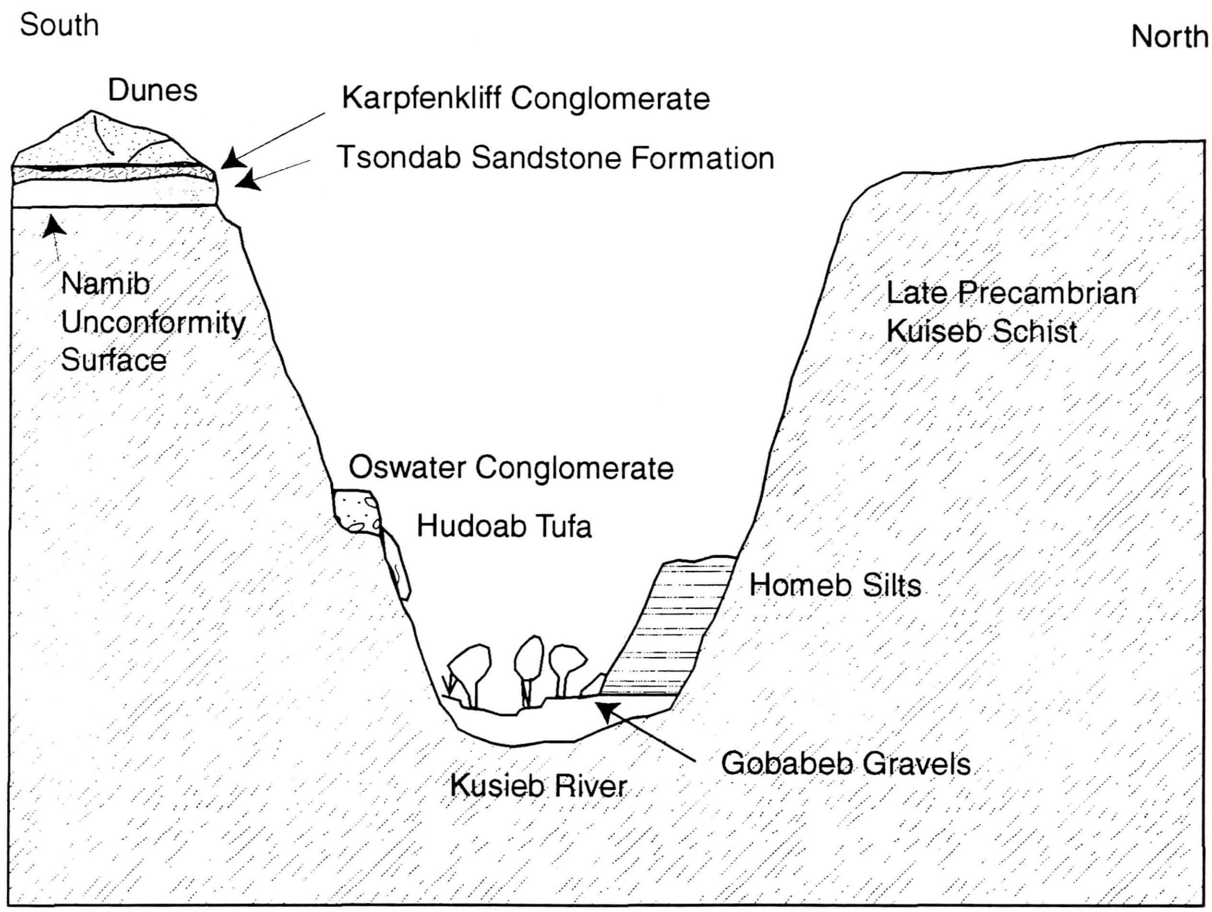

South
North
Dunes
Karpfenkliff Conglomerate
Tsondab Sandstone Formation
Namib Unconformity Surface
Late Precambrian Kuiseb Schist
Oswater Conglomerate
Hudoab Tufa
Homeb Silts
Gobabeb Gravels
Kusieb River

Fig 11

5. THE NAMIB SAND SEA

LOCATION AND ACCESSIBILITY

The main Namib Sand Sea occupies an area of approximately 34,000 km^2 between Luderitz and the Kuiseb River and the coast and the base of the Great Escarpment. Most of the sand seas lies within the Namib-Naukluft Park and is not accessible. The margins of the sand sea can, however, be viewed at many localities, including Luderitz (crescentic dunes and barchans), Sossus Vlei (star dunes), Homeb and Gobabeb (linear dunes), and Walvis Bay/Sandwich Harbor (crescentic dunes and barchans). Access to the interior of sand sea requires 4WD vehicles and special permission from the Namibian Ministry of Environment and Tourism.

SIGNIFICANCE

The Namib Sand Sea is one of the most studied of the major sand seas of the world and contains examples of most major dune (Besler, 1976; Besler, 1980) Lancaster, 1983b; Livingstone, 1986; Livingstone, 1989; Livingstone, 1993). The geomorphology and sediments of the sand sea and its dunes are discussed in detail in Lancaster (1989) and references therein.

GEOLOGY AND GEOMORPHOLOGY

The Namib Sand Sea (Fig. 12) is characterized by a well-organized dune pattern in which crescentic dunes occur in unidirectional wind regimes near the coast; compound and complex linear dunes are associated with bi-directional winds inland; and star dunes with multi-directional wind regimes along the eastern margin of the sand sea (Lancaster, 1983a). Dune height and spacing vary together in a systematic way in the Namib Sand. Dunes are highest (at 100 m or more) and most widely spaced in the central and some northern parts of the sand sea, with progressively lower and more closely spaced dunes towards the margins. The thickness of sand over most of the central parts of the sand sea exceeds 20 m and is more than 30 m north and northwest of Sossus Vlei. Apart from small areas of star dunes, equivalent sand thickness in the southern parts of the sand sea is less than 10 m.

There is a consistent pattern in grain size and sorting parameters with fine, well sorted, near symmetrical sands in central and northern areas of the sand sea and coarser, less well sorted sands in southern and some western parts. There is also an area of coarser, but very well sorted sand, centered on Sossus Vlei. The patterns are best explained by sand movement away from source zones to the south and west of the sand sea during which coarse grains are left behind in upwind areas.

Sources of sand

The dune sands are dominated by quartz (90 %) with feldspar comprising 10 % or less of the total. Their heavy mineral assemblage is dominated by clinopyroxene, garnet and opaque minerals (e.g. magnetite, ilmenite). Sands from the inner shelf north of the Olifants and Orange Rivers have a composition very similar to those of the Namib Sand Sea, with dominant clinopyroxene, garnet and opaques (especially magnetite and illmenite) and traces of other minerals (Lancaster and Ollier, 1983). Outcrops of the Tsondab Sandstone Formation along the eastern margin of the sand sea may be an important local source for dune sands, but its mineralogy suggests that it is not a major source of sand for the sand sea as a whole, in contrast to the view of (Besler, 1980). Grain size and mineralogic evidence suggests that sediments derived ultimately from the Orange River provided the sand for the Namib Sand Sea, in agreement with many early workers in the region (Rogers, 1977). Vigorous longshore drift carries sand-sized material northwards to four main coastal locations from which sand is moved inland in distinct aeolian transport corridors by strong and persistent southerly winds (Corbett, 1993). Changes in sea level resulting from glacial-interglacial cycles gave rise to a different coastal configuration and thus to shifts in the position of the sand transport corridors that fed the sand sea (Corbett, 1993).

Age of the Namib Sand Sea

Estimates of the age of the Namib Sand Sea have varied widely from Pleistocene - Recent (Besler, 1980; Ollier, 1977) to late Pliocene (Ward and Corbett, 1990; Ward et al., 1983). The present-day hyperaridity in the region originated in the Late Miocene (10 - 7 Ma) (Siesser, 1980), following a Middle or Late Miocene period of wetter climates in which fluvial gravels were deposited along major river valleys and pedogenic calcretes formed in gravels and the Tsondab Sandstone Formation (Ward and Corbett, 1990). The dunes of the sand sea unconformably overlie these deposits and the maximum age for the sand sea is therefore Late Miocene, based on stratigraphic relations. The biostratigraphy based on shells of giant avians indicates, however, that unconsolidated sands are associated with shells of *Struthio camelus* (the modern ostrich) and are therefore Quaternary in age. They overlie arenites that contain shells of Post-Miocene avians (Pickford et al., 1995). The sand sea is therefore likely Quaternary in age.

Stop 5.1: Sossus Vlei

Sossus Vlei lies at the western end of the Tsauchab Valley, 64 km from Sesriem (lodge, campsite, small store, gas and diesel. Sesriem is reached via highway #36 from Maltahöhe (or Walvis Bay). A tourist permit from the Namib Naufluft Park is required to visit Sossus Vlei. There is an interesting side trip to Sesriem Canyon. A useful general guide to the area is "Touring Sesriem and Sossus Vlei" by P and M. Bridgeford (1997), which is available from stores at Sesriem.

The Tsauchab Valley is one of several valleys occupied by ephemeral rivers that penetrate the Namib Sand Sea from the escarpment area to the east. Adjacent to the valley are some of the largest dunes in the Namib, and fine examples of star dunes. Sossus Vlei is reached by driving 59 km WSW from Sesriem on a gravel road (cars OK), and then taking a 4WD shuttle or walking the 6 km to the vlei if you do not have a 4WD vehicle.

Sesriem Canyon lies 4 km south of Sesriem village. It comprises a narrow gorge cut by headward erosion of the former Tsauchab River into calcrete-cemented fluvial gravels, sands, and silts (Fig. 13) deposited by a predecessor of the present river. The gorge ranges in width from several hundred meters to only 2 m and extends for about 1 km and is about 30 m (six riem, or thongs) deep. The sediments exposed at Sesriem are probably equivalent to similar late Tertiary or early Pleistocene calcrete-cemented fluvial gravels and sands in the Tsondab and Kuiseb valleys (see below).

Sossus Vlei (Fig. 14) is the present end point of the Tsauchab River (catchment area 4000 km^2), which heads in the Zaris and Naukluft Mountains. The westward course of the river is blocked by star and linear dunes that are 50 – 100 m high. In addition to the present terminal playa, there are numerous other terminal playas amongst the star dunes in this area. These playas represent former endpoints of the Tsauchab River, some 50 km from the sea. Abandonment of the alternative terminal playas was probably the result of blocking of the lower course of the Tsauchab River by dunes. This could indicate lengthy dry periods that resulted in dune enchroachment on the valley.

The Sossus Vlei area has received little detailed study. (Van Zinderen Bakker, 1984), recognized 11 silt beds with a thickness of 2 to 40 cm each in a 3 m-deep pit dug on the east side of the vlei. Interstratified with the silts was red-brown aeolian sand. The composition of the pollen extracted from the silts is similar to modern samples, indicating continued aridity in the region. The non-arboreal pollen (NAP) is dominated by *Chenopodiacae* (75.6 – 80.8%), mostly from *Salsola* spp. that grow along the lower Tsauchab valley. Other NAP consists of Compositae (6.4 – 27.3 %), with lesser amounts of graminae. Pollen from the !Nara plant (*bushes (Acanthosicyos horrida*) is also important (0.5 – 19.7%). Arboreal pollen is dominated by *Acacia* spp.

The age of the sampled deposits was given by Van Zinderen Bakker (1984) as

9 to 16 ka, but in a later publication (Van Zinderen Bakker and Müller, 1987) confusion between the location of radiocarbon dated materials and the studied site is acknowledged. An age of 750±50 yr. (Pta-3822) is given for a silt layer at 1.2 – 1;6 m depth.

Heine (1987) provides some reconnaissance-level data on geomorphic and stratigraphic relations between the modern dunes, playa deposits, and partly indurated red-brown cross-bedded sand of probable aeolian origin (Fig.14). The sandstone does not appear to be an equivalent of the Tsondab Sandstone Formation. Considerable amounts of erosion by fluvial processes and/or aeolian processes are indicated.

Dead Vlei lies 1 km east of Sossus Vlei and is a good example of one of the abandoned terminal playas of the Tsauchab River. It lies at an elevation of m, but is separated from the main terminal playa area by a series of dunes up to m high.

The playa is characterized by 10 – 30 cm of silts that overlie as much as m of semi-consolidated red-brown sandstone (Heine, 1987). The silts have radiocarbon ages of 9460±90 and 9600±90 yr. B.P. (Pta-1503, 1599) (Vogel and Visser, 1981). Similar terminal playa silts also occur in the Tsondab Valley, where they have radiocarbon ages of ... The prominent dead trees at this location have been dated to 525±50 and 575±40 yr. B.P. ((Vogel and Visser, 1981). Their death at this time indicates lowering of the water table in this area, perhaps as a result of regional drought.

Dunes in the vicinity of Sossus Vlei consist of very large star dunes and chains of star dunes, 200 to 350 m high, with small crescentic and reversing dunes around the terminal playas. The dunes have formed in a multi-directional wind regime characterized by SW to WSW winds during summer months, and easterly winds during the winter. The dunes are typically composed of fine to very fine very well sorted yellowish-red rounded quartz sand. Mean grain size is 2.23 phi, with a phi sorting value of 0.28 (Lancaster, 1989). Lower flanks of the star dunes and some sand sheets in this area are characterized by accumulations of coarse grey sand derived from the Tsauchab valley.

Stop 5.2: Linear Dunes south of Gobabeb

The area south of Gobabeb contains many examples of the large, complex linear dunes that dominate the central and northern areas of the Namib Sand Sea. In this area, linear dunes are typically 50 – 100 m high and 800 – 1000 m wide, with a crest to crest spacing of 1000 – 2500 m. Interdune areas are non-depositional to the north, and sand covered to the south.

The crestline of the main ridge is sharp and sinuous and connects a series of regularly spaced peaks. The major slip face, at an angle of 32-33^{0}, faces east or north east and may be 10 m high at the time of its maximum development in March. In winter, east to north east winds erode its upper section and reverse the orientation of the slip face to face west or south west. However, this slip face is rarely more than 5 m high (Livingstone, 1989). Below the slip faces on the eastern side of the dune is a wide, sparsely vegetated, gently sloping plinth. Secondary or superimposed dunes of barchanoid or crescentic form, 2-10 m high and 50-200 m apart, are developed on the upper parts of the plinth (Livingstone, 1987). Strong development of east flank barchanoid dunes is associated with a sinuous main crest. Where it is straight, or slightly sinuous, such dunes are absent or poorly developed. Western slopes and plinths of the linear dunes are smooth or gently undulating in a direction normal to the main dune trend. Slope angles increase from 2-5^{0} on the plinth to 15-20^{0} near the crest. Most interdune areas between complex linear dunes in the Namib are sand covered with undulations on a trend normal or slightly oblique to that of the main dune ridges. In places, these undulations continue onto the plinths and upper western slopes of the adjacent linear dunes.

Linear dunes in the Namib Sand Sea are composed of fine to medium sand with a mean grain size varying from 1.80 to 2.75 phi (0.27 to 0.15 mm). There is a steady decrease in mean grain size from interdunes to the crest and slip face. On complex linear dunes, mean grain size decreases from 1.96-1.98 phi (0.25-0.26 mm) in interdunes through 2.01-2.07 phi (0.24-0.25 mm) on the plinths to 2.35-2.45 phi (0.18-0.20 mm) on upper windward slopes and 2.49 phi (0.18 mm) on the crests. Sand is still finer, at 2.51 phi in the mid slip face position, but coarser (mgs 2.32 phi, 0.22 mm) at the base of the slip face. Often, western plinth sands tend to be slightly coarser than those from the eastern plinth. Sand from crests of superimposed barchanoid dunes on the east flank of complex linear dunes is very similar (mgs = 2.44 phi) to that of the upper parts of the dune with which they are linked.

Stop 5.3: Khommabes

Khommabes is located 5 km NW of Gobabeb, in an interdune corridor on the south bank of the Kuiseb River at 23°32'S, 14°49'S. The site can be reached from Gobabeb as follows:

Km 0	Exit Gobabeb to Kuiseb River. Turn right (downstream). Follow river bed northwest.
Km 7.8	Track to Khommabes exits river on south side through riparian vegetation. Turn left onto this track.
Km 8.5	Proceed around west side of small pan last flooded in 1934.

6. GRAVEL PLAINS OF THE CENTRAL NAMIB DESERT

LOCATION AND ACCESSIBILITY

Most of the central Namib lies within the Namib-Naukluft Park. The area is traversed by the main Maltahöhe – Walvis Bay road, as well as a secondary road from Swakopmund to Windhoek via the Us Pass. Other roads lead south to Gobabeb and Homeb on the Kuiseb River and north to Ganab. A tourist permit is required from the Ministry of Environment and Tourism, Government of the Republic of Namibia, to travel on the park roads and to camp at any campsite or visit any of the sites described below.

SIGNIFICANCE

The central and much of the northern Namib Desert north of the Kuiseb River is characterized by extensive low relief rocky desert plains, with shallow washes and scattered inselbergs. The surface rises gently eastwards from the coast to the base of the Great Escarpment at approximately 1000 m elevation. The origins of the plain and its inselbergs have been discussed at length by numerous authors, e.g. (Hövermann, 1978; Ollier, 1978; Selby, 1977a).

The central Namib Plain has been regarded as a pediplain, cut by steady retreat of the escarpment following break-up of Gondwanaland, some 128 Ma ago (Ward et al., 1983). This model has recently been challenged by data from in-situ cosmogenic isotope studies conducted in the region (Cockburn, 1998). Cockburn (1998) estimated rates of escarpment retreat on the Gamsberg of ~10m Ma^{-1}, using measurements of cosmogenic ^{10}Be and ^{26}Al in quartz. These data are inconsistent with a uniform rate of escarpment retreat from the coast over the past 130 Ma, but are consistent with data from apatite fission track thermochronology which suggest a rapid retreat of the escarpment soon after rifting, but little retreat during the Tertiary (Brown et al., 1990).

Stop 6.1: Mirabib

Mirabib is the location of one of the few stratified archaeological sites in the Namib and was excavated in 1973 and described by Sandelowsky (1977). Evidence for human occupation of the site is restricted to the past 8,500 yr., but the rich archaeological record provides valuable information on human occupation and Holocene paleoenvironments in this region.

The site of Mirabib is located at approximately 23 30 S, 15 E in the east-central part of the Namib-Naukluft Park and is situated approximately 2 km south of the gravel road that runs from the Zebra Pan turn off to Gobabeb. To reach the site, drive 21 km west from the Kuiseb Bridge and take the signed turn off for Zebra Pan, Homeb, and Gobabeb. 10 km from this junction, take the signed road towards Gobabeb. After passing the Tropic of Capricorn (16 km from main road), continue for 11 km (total of 27 km from the main road). At this point, note the prominent granite inselberg of Mirabib Hill on the north side of the road, where there are several camp sites and pit toilets. The site lies approximately 2 km south of the road in a smaller inselberg and can only be reached on foot. Park on the road to the campground and retrace your steps east to pick up an abandoned road that leads south to the site. Walk this road to the rock shelter.

The site of Mirabib is located in a rock shelter on the south side of the inselberg. The deposit is thin (around 0.85 m), but well stratified. Table 3 summarizes the stratigraphy and characteristics of the deposits. The deposit is characterized by several dung layers, abundant plant material including wood, bark, twigs, grass, and seeds of the !nara plant and *Ricinis communis*. Artefacts include granite grinding stones, quartz microliths, ostrich eggshell beads, human hair with ochre, a small amount of pottery, marine shells, bone artefacts, and several copper items. The site was occupied from around 8,400 B.P. to 1,500 B.P., and probably subsequently. The dung layers indicate sheep herding in this area, while the marine shells suggest contact with the coast (100 km away).

A sample of micromammalian bones from Mirabib that dates to within the last 6000 yr was studied by (Brain and Brain, 1977). The presence of *Malacothrix typica* and a higher frequency of gerbils in all but the uppermost units suggest that a more favorable habitat, with moister conditions and more grass cover was present until recently. Drier conditions than those in the area today have occurred twice in the past 500 yr. A period with a climate similar to today was centered around 5,200 B.P.

Table 2: Stratigraphy of depsoits at Mairabib. Adapted and summarized from (Sandelowsky, 1977).

Depth	Characteristics of stratigraphic unit
0–10 cm	Loose brown-grey aeolian sand, grus, and ash. Very disturbed.
10–20 cm	Dung floors interstratified with fine sand. 1550±50 B.P. (Pta-1535)
20-35 cm	Vegetation-rich layer. Sand, ash, charcoal, grus, grinding stones, ostrich eggshells. Numerous artefacts and grass remains. 5190±75 B.P.(Pta-1011).
35-60 cm	Brown-grey sand (aeolian) with artefacts and well-preserved organic matter. Artefacts and ostrich egg shell. Charcoal lenses dated to 6,470±80 B.P.(Pta-1012) and 5,570±50 B.P. (Pta- 1348).
60-75 cm	Dark grey gritty sand (mixture of aeolian sand and grus). Very weathered organic matter and artefacts. Charcoal dates: 8,200±80 B.P.(Pta-1013); 8,410±80 B.P. (Pta-1368); 6,330±60 B.P. (Pta-1347). Possible contamination or intrusion from younger layer above (Sandelowsky, 1977); 6,500±75 B.P. (Pta-1536)
75-80 cm	Red, fine sand (Namib dune sand?), with high percentage of mica in hollows in bedrock.
> 85 cm	Decomposed granite

Stop 6.2: Gypsum Formation in the Central Namib

Gypsum is widely distributed in the central Namib and is frequently used as a road building material. Any of the many borrow pits is likely to provide interesting exposures of gypsum. Good localities lie along the road that follows the water pipeline on the north side of the Kuiseb River southeast of Rooibank. Rooibank is 31 km SE of Walvis Bay and is reached via a good gravel road that leaves the main Walvis Bay – Maltahöhe road 9.5 km east of the Walvis Bay traffic circle. At Rooibank, turn left onto road that parallels the Kuiseb River, and follow road for 3.5 km.

Accumulations of gypsum ($CaSO_4$) are widespread and of considerable thickness in the central Namib Desert (Eckardt, 1996; Watson, 1985). The origins of the gypsum have been explained by many workers in the region (e.g. Goudie, 1972; Heine and Walter, 1996; Watson, 1985) by reference to the model of Martin (1963), who suggested that the gypsum was produced by in situ authigenic alteration of calcium carbonate in calcretes by addition of sulfur. The source of the sulfur was believed to be marine organic sediments deposited offshore in association with upwelling in the Benguela Current system off Walvis Bay, Frequent releases of biogenic H_2S to the atmosphere are carried inland and precipitated by the coastal fog in this region.

Recent remote sensing and field studies by Eckardt (1996) have shown the widespread nature of gypsum in the region and the importance of playas on the gravel plains as sources of gypsum, which is then redistributed by strong northeasterly winds. Studies of coastal fog water chemistry show it to be very pure, with a TDS of only 14.52 ppm, indicating that it is not a source of sulfur in this system. Dry deposition of marine aerosols is probably more effective at introducing sulfur to the region. Sulfur isotope ratio studies (Eckardt, 1996) show that there is no association between the gaseous products of marine organic decomposition and terrestrial gypsum and that the major sources of the sulfur in gypsum are marine dimethyl sulphide (CH_3 SCH_3) from phytoplankton production, and sea spray (SO_4). This material is deposited on the desert surface and enters the soil via rain and fog precipitation. Runoff redistributes marine aerosols and gypsum to playas, with possible contributions from weathering of Damara bedrock. Gypsum is precipitated during evolution of brines in playas and coastal sabkhas, from which it is deflated by strong winds. The origins of gypsum and processes of its accumulation in soils and sediments in the central Namib are therefore similar to those occurring in other deserts (Fig. 17).

Stop 6.3: Vogelfederberg

Volgelfederberg is a prominent granite inselberg (bornhardt) that lies 48 km east of the Walvis Bay traffic circle on the road to Maltahöhe across the Namib-Naukluft Park. This stop permits examination of granite inselberg morphology and weathering processes.

Inselbergs in the Namib have been studied by Ollier (1977) and Selby, (1977a; 1982). Both Ollier and Selby conclude that the form of the inselbergs is structurally controlled by joint patterns. Many of the inselbergs are formed in resistant rocks, compared to surrounding areas. Typically the inselbergs are surrounded by a low-angle pediment, which has a thin cover of angular gravel. The slopes of the inselberg are determined by rock mass strength (Selby, 1982). There are three main hypotheses for the origin of the inselbergs:

(1) Stripping of a weathered regolith to leave residual rock masses. This is regarded as unlikely because of the absence of any chemically weathered regolith exceeding 1 m depth (Selby, 1977a) and the long duration of arid climates in the region.

(2) Successive bevelling of the Namib Plain by mantle-controlled planation (Ollier, 1977). This may be a valid hypothesis where there are lithological differences between the inselbergs and the surrounding plains, but the absence of deep weathering in the area suggests that this hypothesis (as originally formulated by Mabbutt (1966)) is not applicable to this area.

(3) Retreat of slopes (Selby, 1982). The strong relations between slope form and rock characteristics suggest that slope processes are responsible for inselberg formation rather than a general lowering of the landscape is a valid model for many inselbergs in the area.

Analysis of *in situ* cosmogenic isotopes (^{10}Be, ^{26}Al) extracted from quartz in the granite from 3 inselbergs (including Vogelfederberg) indicate mean rates of summit lowering ranging between 2.3 to 6.3 m Ma^{-1} over the past $1 - 3 \times 10^{-5}$ yr (Cockburn, 1998). These data tend to support the slope retreat model above.

Weathering processes on Namib inselbergs include unloading, surface flaking, granular disintegration, and formation of tafoni (prominent at Vogelfederberg) (Ollier, 1978). Tafoni formation has been studied in detail by (Goudie and Migón, 1997).

Stop 6.4: Ventifacts at Swartbank

Prominent and well-developed wind erosion flutes, grooves, and polished and etched surfaces are found on outcrops of Precambrian marble of the Karibib

Formation that occur just south of Swartbank Mountain, adjacent to the road from Gobabeb to Rooibank. The ventifacts are found in association with rillenkarren developed on the marble. The location can be reached by driving 39.2 km northwest from Gobabeb along the gravel road that follows the Kuiseb River from Gobabeb to Rooibank.

Wind erosion features are widespread in the Namib Desert. Large scale features including yardangs developed in Precambrian marble and foyaite and Proterozoic dolomite occur in the southern Namib (Corbett, 1993; Kaiser, 1926; McCauley et al., 1977). In the central and northern Namib, the most widely developed features of wind erosion include etching of lithological inhomogeneities, smoothing and polishing of rock surfaces, flutes and grooves, and facetting of outcrops and clasts (Lancaster, 1984). In the central Namib, most wind erosion features occur on the north and east sides of rock surfaces. They are oriented to face the direction from which the strongest winds in this area blow (Selby, 1977b), rather than the more persistent, but weaker, SSW to SW winds. Wind erosion features are best developed on fine-grained rocks of intermediate hardness, such as dolerite, marble, dolomite, and limestone (Table 3). They are rarely developed on coarse grained rocks, or those that are weathered readily (e.g. schist and most granites).

The locality at Swartbank permits examination of wind erosion and limestone solution features described by (Sweeting and Lancaster, 1982). The features occur on a NE – SW trending outcrop of marble that is manifested as a series of 1 – 3 m high boulders. The east and northeast sides of these boulders are extensively wind eroded, in contrast to the west and north sides, which have a weathered patina and algae and lichen crusts. Rillenkarren similar in morphometry to those found in other areas of limestone occur on the northwest-facing rock surfaces. They are typically 22 – 30 mm wide, rounded in cross section, and extend down slope. By contrast, wind erosion flutes on the eastern sides of these boulders are aligned NE – SW, cross the boulder surfaces at an angle to the local slope, and are sharp in appearance. Typical wind erosion flutes are 5.65 mm wide and 2 mm deep. The orientation of the flutes and grooves is similar to that of facets developed on dolerite clasts north of Swartbank Mountain (Selby, 1977b). The fresh nature of the rillenkarren and wind erosion flutes suggestes that they are forming today. Rillenkarren development is the result of high rates of precipitation of advective fog on northwest facing rock slopes. The nearby weather station receives mm of fog precipitation each year in many cases accompanied by winds from the northwest (Lancaster et al., 1984).

Strong winds in this area are from the northeast: 84% of winds with a speed greater than 11 m/sec at a height of 3 m are from this directional sector.

Table 3: Ventifact Orientations in the Namib Desert From Lancaster (1984)

Site	Lithology	Orientation
Pomona	Dolomite, foyaite, silcrete	SSE – SSW
Kolmanskop	Geniss, metaquartzite	SSE – SSW
Sylvia Hill	Calcareous schist	SSE – SSW
Uri Hauchab	Metavolcanic	NE
Conception	Granite	SSW
Tsondab	Dolomite, limestone (alluvial clasts)	SW and NE
Swartbank	Dolerite, marble	NE
Swakop River	Marble	SW
Henties Bay	Dolerite	NE
Cape Cross	Basalt	NNE
Skeleton Coast	granite	SSW - SW

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6. RAISED BEACH DEPOSITS OF THE CENTRAL NAMIB COAST

LOCATION AND ACCESSIBILITY

The Namib coast north of the sand sea is readily accessible via gravel and paved roads that parallel the coast. Two of the main towns of Namibia, Walvis Bay (its main port), and Swakopmund (an important tourist town) are located in the region of interest. Both centers offer all facilities including a range of hotel and resort accomodations, gas stations, stores, etc.

SIGNIFICANCE

The southern Namib coast is well known for its Tertiary and Pleistocene littoral deposits, some of which are diamondiferous (Pether, 1986). Similar shorelines are poorly exposed or not present in the central Namib Desert. One of the best exposed of these sedimentary units is the Rooikop Gravels, first described by Miller and Seely (1976).

GEOLOGY

Stop 6.1: Rooikop Gravels

The type locality of the Rooikop Gravel is located approximately 10 km east of Walvis Bay. To reach this stop, leave Walvis Bay to the east on the Maltahöhe road (C14) and follow these directions:.

Km 0 Traffic circle

Km 8 Junction with road to dunes on left. Signed "Dune 7". Turn left (north).

Km 9.5 Railroad crossing. Immediately before this crossing turn sharp right onto road that parallels water pipeline and powerline from Rooibank.

Km 10.5 Park on edge of road and walk 50 m south to borrow pit and exposure of Rooikop Gravel and included shells of *Striostrea magaritacea* and *Donax rogersi*. Note: there are many small exposures of this sedimentary unit in the scattered gravel pits and excavations in this area. Many of these pits are filled with wind blown sand, which may obscure the unit.

Retrace route to main (paved) road.

Gypsiferous sandy to gravel deposits that contain oyster shells are exposed in the area east of Walvis Bay, near the southern tip of the Walvis Bay-Swakopmund dune belt, at elevations of 15 – 40 m above sea level (Miller and Seely, 1976; Ward, 1987). The deposits are 0.5 to 2 m thick and directly overlie Damara granite and Tertiary arenites and grits. They consist of horizontally-stratified well-rounded cobble to pebble gravel, sand, greenish grey gypsiferous clay, and oyster shells in a matrix of pinkish brown gypsum.

This sedimentary unit was interpreted as a littoral deposit formed in a shallow marine embayment or tidal lagoon by (Miller and Seely, 1976). The terrestrial gravels were derived from the Swakop and Kuiseb rivers and reworked by wave action. The presence of shells of the robust oyster *Striostrea margaritacea* indicates warmer ocean temperatures than at present.

The age of the Rooikop gravels is uncertain. Radiocarbon dates of 30 – 35,000 B.P. obtained by Rust and Weinecke, (1976) are considered suspect by SACS (1980) and Ward (1987). Similar oyster-bearing marine gravels have been identified in the southern Namib and Namaqualand, where they were assigned a Miocene age (see discussion in Ward, 1987). Recent work by Pether (1986) has, however, identified two major marine sedimentary units: an early Pleistocene transgressive package at 30 m elevation and a late Pliocene regressive package at 50 m elevation. The 30 m package is characterized by the zone fossil *Donax rogersi*, which has also been found at Rooikop, suggesting that the Rooikop gravels are of early Pleistocene age.

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