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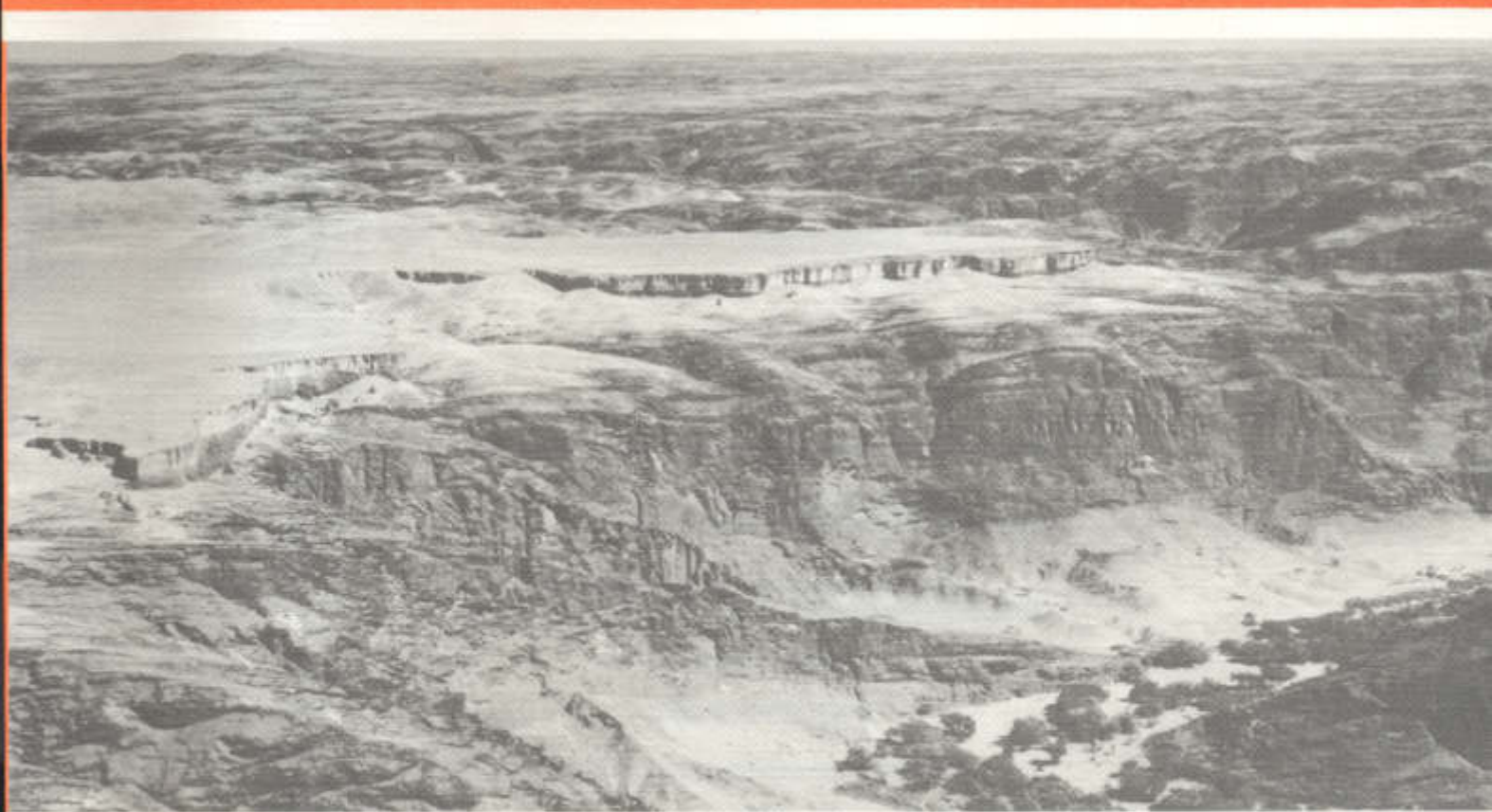
SOUTH WEST AFRICA/NAMIBIA  
SUIDWES-AFRIKA/NAMIBIË



**THE CENOZOIC SUCCESSION IN THE KUISEB VALLEY,  
CENTRAL NAMIB DESERT**

by

**J.D. WARD**



**MEMOIR 9  
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**GEOLOGICAL SURVEY OF SOUTH WEST AFRICA/NAMIBIA  
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## ABSTRACT

The Kuiseb River, an ephemeral watercourse, demarcates the northern boundary of the main Namib Sand Sea, except in the coastal tract where dunes extend from the Kuiseb Delta northwards in a narrow belt to the Swakop River. This study addressed the nature of this boundary with respect to the Cenozoic history of the Kuiseb Valley west of the Escarpment. The Cenozoic succession consists of ten sedimentary units; their nomenclature, distribution, composition, origin, age and correlation are presented here. A new lithostratigraphic, and provisional geochronologic, framework is also proposed. The accumulation of this Cenozoic succession reflects five major events that affected the Namib tract, viz.:-

i) post-Gondwana erosion phase: pediplanation processes bevelled the Late Precambrian bedrock (or exhumed a pre-Karoo surface) to an extensive platform - the Namib Unconformity Surface - on which the Cenozoic deposits accumulated;

ii) proto-Namib palaeo-desert phase: during much of the Palaeogene, an arid phase prevailed resulting in the deposition of a thicker and more extensive cover of desert-related sediments (Tsondab Sandstone Formation) than that in the modern Namib Sand Sea (Sossus Sand Formation);

iii) Karpfenkliff fluvial phase: a change, probably in the Miocene, to a more humid, but nevertheless semi-arid, climate initiated the development of a competent, but still not deeply incised, drainage system (Kuisseb-Gaub) west of the Escarpment (Karpfenkliff Conglomerate Formation). A high stand in sea level during this period is recorded by the basal marine deposits of the Rooikop gravels;

iv) pedogenic phase: at the end of the Miocene, a semi-arid climate and landform stability promoted the development of pedogenic calcretes (Kamberg Calcrete Formation) in the uppermost sediments of the Tsondab and Karpfenkliff Formations.

v) Namib Desert phase: the present extreme-arid conditions developed progressively, with minor humid fluctuations, through the Late Cenozoic, following on the establishment of the cold-water Benguela Current System in the Late Miocene. The accumulation, therefore, of the Sossus Sand Formation probably dates from the Pliocene. The deep incision by the Kuiseb drainage system was probably initiated by epeirogenic uplift at the end of the Tertiary and the subsequent Quaternary history of this river reflects several alternating aggradational and erosional stages.

The Oswater Conglomerate Formation (Early Pleistocene) represents the initial aggradational stage and also provides the first record of an association between Sossus Formation dunes and the incised Kuiseb River. The second aggradational stage is marked by sediments of the Homeb Silt Formation and the Awa-gamteb muds (Late Pleistocene). During the ensuing re-incision stage, at the end of the Pleistocene, fluvial sediments of the Gobabeb Gravel Formation were deposited.

During the Quaternary, the predominantly arid climate of the Namib was punctuated by short-lived, more humid intervals when pan deposits of the Khommabes Carbonate Member of the Sossus Formation accumulated and the calcareous material of the Hudaob Tufa Formation was precipitated at localised spring/seep sites.

The Kuiseb River has formed the northern boundary of the main Namib Sand Sea since at least Oswater times, except along the lowermost 40 km of its course. In that region, the Kuiseb appears to have been displaced c. 30km northwards, from Sandwich Harbour to its present position.

This displacement was probably a consequence of dune encroachment from the south into a comparatively shallow, open valley, and was facilitated by the ephemeral hydrological regime of the Kuiseb River that has prevailed throughout the Quaternary.

## 1. INTRODUCTION

### 1.1 General

The Kuiseb River, rising on the interior plateau of central South West Africa/Namibia some 20 km south-west of Windhoek, is one of the major ephemeral watercourses traversing the Namib Desert towards the Atlantic Ocean (Fig. 1). In its upper reach on the plateau, the Kuiseb follows a sinuous course shallowly incised into Late Precambrian metasediments of the Damara Sequence. West of the Escarpment, it occupies a spectacular, deeply incised gorge, cut into similar metasediments, which opens up some 65 km from the coast. Thereafter, the river lies in a shallow valley, carved in Late Precambrian metasediments and Cambrian granites, that broadens downstream to some 1-2 km wide between 20 and 40 km from the coast. The lowermost reach consists of poorly defined channels terminating on the coastal flats in the vicinity of Walvis Bay. Large linear dunes front onto the left flank of the Kuiseb Valley from the canyon reach downstream to Rooibank, some 20 km from the Atlantic Ocean. Crescentic dunes are associated with the lowermost Kuiseb course from about Rooibank on to the coastal flats.

The Kuiseb drainage system is cut into Late Precambrian rocks, most of which belong to the Damara Sequence (Fig. 2). Two outcrops of Etjo Formation quartzites (Jurassic age) form resistant cappings, the Gamsberg (2 347 m) and Klein Gamsberg (2 236 m), the highest points of the Great Escarpment. Dolerite dykes, also of Jurassic age, have intruded the Precambrian rocks within the Namib tract to the west of the Escarpment. A major unconformity separates these older rock types from the surficial deposits preserved in the Kuiseb drainage system, the bulk of which occur to the west of the Escarpment (Fig. 2). These surficial deposits are considered to be Tertiary to Quaternary in age (Geological map of SWA/Namibia, 1980).

The geological succession occurring in the Kuiseb drainage system (Fig. 2) can be summarised as:

- (ii) Cenozoic surficial deposits major unconformity
- (i) Precambrian and Cambrian rocks, chiefly of the Damara Sequence; locally overlain by quartzite of the Etjo Formation (Karoo Sequence) and intruded by dolerite dykes of Jurassic age.

West of the Escarpment, the Kuiseb River forms the northern boundary of the main Namib Sand Sea, with the exception of the coastal tract, where crescentic dunes form a narrow belt extending northwards from the Kuiseb Delta to the Swakop River. Alexander (1838, reprinted 1967) first recorded the termination of dunes along the lower Kuiseb Valley, a boundary relationship that is well illustrated by satellite imagery covering the Central Namib Desert (Fig. 3).

### 1.2 Previous Work

The earliest reports, which incorporated geomorphological aspects of the Kuiseb River, date back to the late 1800s (Stapff, 1887; Wilmer, 1893) and were followed by the observations of Gevers (1936), Korn and Martin (1937, 1957), Martin (1950, 1957, reprinted 1974, p. 68-70, 153-155), Logan (1960) and Spreitzer (1966). More recent investigations include those of

Goudie (1972), Barnard (1973, 1975), Besler (1977, 1980, 1984), Selby (1976, 1977), Marker (1977, 1979/81, 1982), Ollier (1977, 1978), Marker and Müller (1978), Besler and Marker (1979), Harmse (1980), McKee (1982), Vogel (1982), Ward (1982, 1984a, b), Yaalon and Ward (1982), Ward *et al.* (1983), Lancaster (1984), Huntley (ed., 1985) and Ward and Von Brunn (1985a, b).

### 1.3 Present Study

#### 1.3.1 General background

The Kuiseb Valley is an ecologically important linear oasis in an otherwise inhospitable desert tract (Seely *et al.*, 1979/81). In recent years, considerable demand has been placed on both the surface (*viz.*, agricultural activity in the catchment region) and the underground (*viz.*, domestic and industrial use in the coastal tract) water resources of the Kuiseb River. For example, a major portion of the freshwater requirements of Walvis Bay, Swakopmund and the Rössing uranium mine complex is drawn from the alluvial aquifer in the lowermost reaches of the Kuiseb River (Myburgh, 1971; Kuiseb Env. Proj. unpubl. rep., 1976; Seely *et al.*, 1979/81; Huntley (ed.), 1985).

This utilisation could lead to environmental problems, including the possibility of the Kuiseb River forfeiting its role both as the northern barrier to dune encroachment from the main Namib Sand Sea and as a viable linear oasis (Seely *et al.*, 1979/81).

A multidisciplinary investigation into hydrological, ecological and geomorphological aspects of the Kuiseb drainage system was therefore carried out from the mid-1970's to the early 1980's under the auspices of the Kuiseb Environmental Project and co-ordinated by the then Co-operative Scientific Programmes section of the Council for Scientific and Industrial Research (CSIR). The aim of the Project was to provide a baseline for monitoring changes in the Lower Kuiseb ecosystem, with particular reference to the status of the riverine vegetation and groundwater reserves, and to the threat of dune migration from the main Namib Sand Sea into and across the river bed. Furthermore, the importance of the Kuiseb River as the northern boundary of the main Namib Sand Sea was to be evaluated.

Geomorphological and geological investigations for the Kuiseb Environmental Project were undertaken by the writer and covered a period of 3 years fieldwork from 1979 to 1981 (Ward, 1984a; Ward and Von Brunn, 1985a, b).

#### 1.3.2 Study area

The study area included the Kuiseb Valley and its major tributaries west of the Great Escarpment as well as the northern section of the main Namib Sand Sea (Fig. 4, which also shows the place names referred to in the text). Many of the place names, notably those along the Kuiseb River downstream from Hudaob, do not appear on published maps of the Central Namib and have been taken from localities known to the indigenous Topnaar people (Ward and Van Wyk, 1985). Another local term used in this report is "gramadulla", coined by Martin (1957, reprinted 1974, p. 65) for the rugged, intensely dissected terrain adjacent to the canyon reach of the Kuiseb and Gaub Rivers.

#### 1.3.3 Course of study and methods used

Initially, aspects of the sand dynamics along the Lower Kuiseb River were monitored, with emphasis on the movement of dunes from the main Namib Sand Sea into the valley (Ward and Von Brunn, 1985b). However, in order to appreciate more fully the boundary relationship between the Lower Kuiseb River and the northern margin of the main Namib Sand Sea in the course of past times, an investigation into the

Cenozoic history of the Kuiseb Valley west of the Great Escarpment was necessary. The results of that part of the study are presented in this report. Previously, the distribution and stratigraphy of the Cenozoic succession in the Central Namib had not been extensively reported on and a consistent nomenclature was, hitherto, lacking.

Fieldwork was supplemented by the interpretation of the aerial photographs of Jobs 774 (1977, scale 1:50000), 746 (1976, scale 1:15 000) and 311 (1978, scale 1:15 000). Limited ground checks of key exposures were undertaken in November-December 1982. The groundwork was supported by oblique aerial photography and observations from a light aircraft (flying height 160 - 600 m).

Outcrop sections were measured with an Abney level, tape and ranging rod. Two altimeters were used to determine the heights of terrace deposits in relation to beacons surveyed by the Department of Water Affairs. For the rudaceous deposits, the size of ten largest clasts was determined at anyone locality using a set of calipers.

Many of the Cenozoic deposits cover a fairly extensive area of the Central Namib Desert. Therefore, their distributions, although mapped at scales ranging from 1:15000 to 1:50 000, were plotted at 1:250 000 for reconnaissance base maps that have subsequently been reduced for convenient incorporation into this report.

During this study, emphasis was placed on fieldwork and consequently laboratory work was kept to a minimum, involving the identification of certain sediment types by means of thin-section microscopy and X-ray diffraction (XRD) analyses. The latter were undertaken by Dr D. Buhmann, in the Department of Geology, University of Natal, Pietermaritzburg. The study was supervised by Professor V. von Brunn, Department of Geology, University of Natal, Pietermaritzburg and logistically supported by the Geological Survey of South West Africa/Namibia.

## 2. THE CENOZOIC SUCCESSION

### 2.1 General

The relatively narrow Namib tract formed as a consequence of the retreat of the Great Escarpment following the break-up of West Gondwana during the Cretaceous (Martin, 1973, 1975; summarised in Ward *et al.*, 1983). The Great Escarpment is an erosional feature and the pediplanation processes associated with its formation, in grading the coastal strip to the Atlantic Ocean, bevelled the predominantly Late Precambrian bedrock into an extensive land surface studded with inselbergs (Martin, 1973; Dingle and Scrutton, 1974). Ollier (1977, 1978) referred to this pediplain as the Namib Unconformity Surface (NUS). The well-planed surface, below which the bedrock is not deeply weathered, was the platform for the initial accumulation of the surficial deposits in the Central Namib Desert (Fig. 5).

From the Niedersachsen-Changans area, near the base of the Escarpment (Fig. 4), the NUS forms a shallow, broad (10-20 km wide) bedrock depression trending southwestwards to the vicinity of Gomkaeb. This depression forms the base of an ancestral valley that was first recognised by Martin (1957, reprinted 1974) and is called here the proto-Kuiseb Valley. Martin (1975) reported the occurrence of a small patch of Dwyka (glacial) sediments on the Farm Komuanab and, on the basis of geomorphological configuration, suggested that the Nausgomab Valley may have been shaped by ice in the Palaeozoic. Consequently, the pre-incised Nausgomab Valley and the apparent concomitant level of the NUS in the adjacent proto-Kuiseb Valley may represent a pre-Karoo erosion surface. At this stage, however, these correlations must remain

speculative as additional fieldwork is needed to resolve this correlation which is beyond the scope of this report.

Nevertheless, the NUS is the fundamental datum for any considerations concerning the age of the Cenozoic succession in the Kuiseb Valley west of the Escarpment. It is believed by some researchers to have formed or to have been exhumed, during the Late Cretaceous (Martin, 1973, 1975; Ollier, 1977, 1978; Ward *et al.*, 1983). In contrast, Selby's (1977) suggestion of a Miocene age is based on the development of arid conditions attendant on the full establishment of the Benguela Current in Late Miocene times (Siesser, 1978, 1980). Partridge (pers. comm., 1983; 1985) also favoured a Miocene age because of the lack of deep bedrock weathering that characterises the older, so-called "African" surface elsewhere in southern Africa.

However, Ward *et al.* (1983) argued that the cold Benguela Current System is not necessarily a prerequisite for arid conditions to prevail in the present Namib tract and Stocken (pers. comm., 1982/83) noted that the bedrock under the End Cretaceous surface in the Southern Namib is not everywhere deeply leached and kaolinised. He also suggested that the bedrock depression of the proto-Kuiseb Valley could be Early Tertiary in age but the presence of an c. 4 km thick wedge of Albian - Maastrichtian sediments in the Walvis Basin offshore of the Central Namib (Dingle *et al.*, 1983, p. 223-225) lends some support to an End Cretaceous age for the NUS.

The sequence in the accumulation of the surficial cover in the Central Namib was best appreciated by Martin (1950; 1957, reprinted 1974, p. 69, 153; 1961) who briefly discussed the Cenozoic deposits in relation to both the Kuiseb Valley and the Namib Desert as a whole. Subsequently, Ollier (1977, 1978) presented a comprehensive outline of the geological and geomorphological history of the Central Namib Desert, including the Kuiseb Valley.

This study has added further detail to the earlier investigations of the Cenozoic succession in the Kuiseb Valley west of the Escarpment. The salient events in the history of the Cenozoic succession outlined by Ollier (1977, 1978) are compared in Table 1 with the observations made during this study. These events, the main points of which are incorporated in Fig. 6, are summarised briefly below.

The NUS is commonly overlain by a thin quartz breccia that grades upwards, over several metres, into a cover of quartzose sandstones up to 220 m thick. The sandstones filling the bedrock depression of the proto-Kuiseb Valley are predominantly carbonate-cemented and capped by calcified conglomerates that wedge out down the regional slope away from the Escarpment. These rudaceous deposits, and the largely uncemented but semi-consolidated sandstone on the adjacent interfluvial areas, are covered by pedogenic calcretes that formed prior to the deep incision of the Kuiseb drainage system west of the Escarpment. A sequence of terrace deposits within the deeply-entrenched courses of the Kuiseb River and its major tributaries provides a record of alternating aggradational and erosional phases that occurred during the post-incision history of the Kuiseb Valley.

The Cenozoic succession in the Kuiseb Valley west of the Escarpment can thus be conveniently subdivided into two main categories relative to the canyon incision (Fig. 6):

- (i) "pre-incision" deposits that accumulated on the NUS;
- (ii) "post-incision" sediments preserved mainly as terrace remnants within the entrenched Kuiseb drainage system.

The general distribution of these two principal subdivi-

sions of the surficial deposits in the Namib sector of the Kuiseb Valley is shown on a small-scale map in Fig. 7.

The incision of deep canyons by the larger rivers draining westwards across the Namib Desert towards the Atlantic Ocean has provisionally been assigned to the end of the Tertiary (Korn and Martin, 1957) which accords with that postulated for the deep incision by the river courses in South Africa (King, 1951, p. 193; Partridge, 1982). Therefore, the pre-incision deposits probably originated during the Tertiary and the post-incision sediments during the Quaternary.

The lithological units identified in the Cenozoic succession are indicated in a stratigraphic table summarising the geology of the Kuiseb drainage system west of the Escarpment (Table 2); formal nomenclature proposed by the author is also incorporated here. The approximate distribution of the units recognised in the Cenozoic cover of the study area are illustrated in the reconnaissance map, Fig. B. 1 (Appendix).

In this report, the lithostratigraphy of the Cenozoic succession is discussed in order from the oldest to the youngest unit (Table 2). A consistent scheme is followed in discussing each lithostratigraphic unit and consideration is given to:

- (i) a general introduction that includes the origin of the name proposed for that deposit and its type locality. The type localities for the formations are summarised in Table B.1 (Appendix);
- (ii) the distribution, illustrated on a reconnaissance map; lower and upper boundary contacts; the thickness of the deposits and, in the case of fluvial deposits, a longitudinal profile;
- (iii) the lithology and sedimentary structures, based primarily on field observations but, in a few cases, supported by XRD analyses (Table B.2, Appendix);
- (iv) the mode of origin; in many instances this is a clarification and expansion of earlier hypotheses;
- (v) age and correlation, which has been difficult to determine because of the lack of fossils, dated marine sediments, and Tertiary igneous rock types such as those found in the Southern Namib (e.g. Stocken, 1978). Correlation with other Cenozoic deposits is confined to the Namib Desert.

In this study, key vertical stratigraphic sections are used to record and present details of the Cenozoic succession, particularly those sediments proposed here as formal lithostratigraphic units. Cognisance was also taken of the potential for lateral facies changes in the Cenozoic deposits. An appreciation of this concept was particularly important when the fluvial deposits were investigated because these could commonly be traced from near the base of the Escarpment (the proximal reach) across the Central Namib tract towards the Atlantic Ocean (distal reach). Therefore, reference sections and longitudinal profiles have been incorporated, where possible, to illustrate the possible effects of such lateral facies changes within the surficial deposits comprising the Cenozoic succession in the Kuiseb Valley west of the Escarpment.

The surficial deposits in the study area comprise (oldest at the base):

#### Post-incision Deposits

Kuiseb River alluvium .....	Sossus Sand Formation
Gobabeb Gravel Formation	including the
Awa-gamteb muds	Khommabes
Homeb Silt Formation	Carbonate Member
Hudaob Tufa Formation	
Oswater Conglomerate Formation	

TABLE 1: Outline of the Late Mesozoic-Cenozoic geological and geomorphological history of the Kuiseb Valley west of the Great Escarpment.

OLLIER (1977; 1978)		PRESENT INVESTIGATION	
		Lithologic Description	Stratigraphic Unit
12.	Formation of minor terraces and present floodplain as well as north-south dunes south of the Kuiseb.	12. Present Kuiseb River; minor terraces and floodplain; coastal salt flats, pans, with low dune formation.	
11.	Formation of the lower terraces.	11. Gravels, locally cemented; characteristic golden-yellow colour of quartz clasts in lower reaches.	Gobabeb gravels.
10.	Re-excitation to bedrock, leaving remnants of Homeb Silts.	10. [ ]	
9.	Deposition of Homeb Silts.	9. Micaceous silts and interbedded river- and dune-derived arenite lenses; silts and coastal pan deposits in Delta region.	Homeb silts Awa-gamteb muds
8.	Erosion to bedrock at present river level.	8. Erosion to bedrock at present river level.	Hudaob tufa
7.	Deposition of gravels of Ossewater Conglomerate to form a terrace. Cementation.	7. Conglomerates; quartz arenites; interbedded aeolianite wedges in downstream outcrops.	Ossewater conglomerate
6.	Cutting of canyon, almost to present level, tributaries form badlands on north bank.	6. Deep incision of Kuiseb drainage system west of Escarpment	? Onset of the accumulation of the main Namib Sand Sea (Sossus Sand Formation) with scattered pan development (Khommbes-type deposits).
5.	Initiation of Kuiseb course on Tsondab Planation Surface or Namib Unconformity Surface.	5. [ ]	
4.	Erosion of Tsondab Planation Surface; pediment with E-W drainage; calcrete conglomerates; possible Middle to Later Tertiary.	4. Widespread pedogenic calcrete development on surficial deposits.	Karpfenkliff conglomerate
3.	Deposition of the Tsondab Sandstone; aeolian dune origin.	3. Widespread arenites; palaeo-dunes and pans; valley fill deposits; ancient alluvium.	Tsondab Sandstone Formation
2.	Deposition of the Basal Conglomerate; locally a breccia or may be absent.	2. Basal breccia.	
1.	Formation of the Namib Unconformity Surface; possibly pre-Upper Cretaceous; no evidence of deep chemical weathering.	1. Ditto; extensively planed bedrock surface with minimal bedrock weathering; possibly End Cretaceous.	

TABLE 2: Principal lithological units encountered in the study area. Emphasis placed on the Cenozoic succession.

ERA	PERIOD	PRINCIPAL GEOLOGICAL UNITS	LITHOLOGY	
CENOZOIC	QUATERNARY	Recent	<ul style="list-style-type: none"> <li>Quartz (&gt; 90%) sands</li> <li>Pebble-cobble lag gravel; minor conglomerate, rolled MSA artefacts</li> <li>Calcium carbonate, calcified reed stalks and leaves, fossils, including <i>Eragrostis</i> reed, rare.</li> <li>Clays, silts, micaceous sands; intercalated quartz sand layers</li> <li>Micaceous silts; minor quartz sand lenses and locally derived conglomerate</li> <li>Calcium carbonate; traces of calcified vegetation</li> <li>Boulder conglomerate (proximal to Great Escarpment);</li> <li>Cobble-boulder conglomerate and interbedded quartz arenite;</li> <li>Pebble conglomerate, arenite lenses and wedges of interbedded oolite (distal reach)</li> </ul>	
		Pleistocene	<ul style="list-style-type: none"> <li>Kuiseb River alluvium</li> <li>Sossus Sand Formation</li> <li>Gobobeb Gravel Formation* including Khommabas Carbonate Member*</li> <li>Awa-gamteb muds*</li> <li>Homeb Silt Formation*</li> <li>Hudob Tufa Formation*</li> <li>Oswater Conglomerate Formation*</li> </ul>	
	TERTIARY	Neogene	<ul style="list-style-type: none"> <li>Unconformity</li> <li>Kamberg Formation*</li> <li>Celcrete</li> <li>Rooikop gravels</li> <li>Karpenkliff Conglomerate Formation*</li> <li>Unconformity</li> </ul>	<ul style="list-style-type: none"> <li>Calcium carbonate in profile: laminar crust (surface) → hardpan calcrite → honeycomb calcrite → nodular calcrite</li> <li>Lithoral gravels; gypsum; oysters (<i>Sfristrea margaritacea</i>);</li> <li>Boulder conglomerate (proximal to Great Escarpment);</li> <li>Cobble-boulder conglomerate and interbedded quartz arenite lenses;</li> <li>Pebble-cobble lag gravels (distal area)</li> </ul>
		Palaeogene	Zebra Pan Carbonate Member*	Carbonate-cemented quartz arenite, red-brown, patterned ground and macro-fractures
			Tsondab Sandstone Formation*	Calcrete-dolomite cemented quartz arenite; rare pebble horizons. Indurated, locally-developed carbonate; mainly dolomite. Uncemented quartz arenite, red-brown; structureless to cross-stratified. Calcrete-dolomite cemented quartz-garnet breccia.
	MESOZOIC	CRETACEOUS	MAIN UNCONFORMITY	Basal 'quartz-rich' breccia (locally absent)
			Dolerite dykes	Dolerite
		JURASSIC	Intrusive	
			Etjo Formation (Karoo Sequence)	Silicified quartz sandstone (quartzites, original sand grains visible in hand specimen).
	PRECAMBRIAN	MAIN UNCONFORMITY	Damara Sequence	Schist; metaquartzite (crystalline), marble; calcisilicate; amphibolite; intrusive granites (Cambrian)
Gamsberg Suite			Granite	
Rehaboth Sequence			Metaquartzite; schist; metaconglomerate; quartz porphyry; intrusive metabasite dyke swarm, quartz diorite and granodiorite	
Ababis (west), Moorivier (east) Complexes			Paragneiss; metasedimentary rocks	

\* FORMER NAMES PROPOSED HERE



### Pre-incision Deposits

Kamberg Calcrete Formation  
 Rooikop gravels (stratigraphic position uncertain)  
 Karpfenkliff Conglomerate Formation  
 Tsondab Sandstone Formation

### Namib Unconformity Surface

## 2.2 Tsondab Sandstone Formation

### 2.2.1 General

The NUS is overlain commonly by a thin (up to 3 m thick) quartz-rich sedimentary breccia that mostly grades upwards into quartz arenites. Where the basal breccia is absent or only poorly-developed, notably on the Salem and Donkerhuk granites associated with the Damara Sequence, reddish-brown arenites rest directly on the NUS. The basal breccia and reddish-brown arenites, therefore, constitute the oldest surficial deposits in the Kuiseb Valley west of the Escarpment, a relationship appreciated by both Martin (1957, reprinted, 1974, p. 69) and Ollier (1977, 1978; Table 1).

Many earlier workers reported the occurrence of reddish-brown arenites underlying the modern dunes of the main Namib Sand Sea, including Martin (1950; 1957 reprinted 1974, p. 68-70; 1973), Goudie (1972), Barnard (1973), Selby (1976, 1977), Besler (1977, 1980), Marker (1977), and Harmse (1980). Ollier (1977, 1978) called these arenites the Tsondab Sandstone, whereas Besler and Marker (1979) proposed the name "Namib Sandstone" because of the widespread distribution of these arenaceous deposits in the Central and Southern Namib. However, these extensive reddish sandstone have been formally designated the Tsondab Sandstone Formation by SACS (1980). The type locality is the 60 - 90 m high reddish sandstone cliffs at Tsondab Vlei (23°55'S and 15°25'E), some 25 km south of the Gomkaeb corner in the Kuiseb canyon (Fig. 3).

Within the study area, the Tsondab Formation comprises six facies designated A - F. Two of these (A, B) are rudaceous, three (C, D, E) arenaceous and one facies (F) is composed of carbonate. Facies C and D comprise reddish-brown arenites typical of the Tsondab Sandstone (SACS, 1980), whereas Facies E is considered a lateral equivalent of Facies C. The thin quartz breccia, resting on the NUS, forms the base of the Tsondab Formation and is formally called the Gomkaeb Basal Breccia Member. Ollier (1977) referred to these deposits as the Basal Conglomerate but the predominantly sub-angular nature of the constituent clasts warrants the use of the term "breccia". The type locality is situated at the Gomkaeb corner (23°42.5'S; 15°27'E), c. 60 km upstream from Gobabeb (Figs. 8:1; 8). Facies F has also been accorded formal status and is known as the Zebra Pan Carbonate Member. The type locality for this member is a small carbonate mesa, c. 15 km south-east of Zebra Pan (Fig. B.1), resting on reddish-brown Tsondab Sandstone between the Kuiseb Canyon and the Kamberg (23°34'S; 15°39'E), (Fig. 8).

### 2.2.2 Distribution and thickness

The Tsondab Sandstone underlies much of the main Namib Sand Sea between about Lüderitz and the Kuiseb River (Martin, 1950, 1973; Besler and Marker, 1979; SACS, 1980). The Kuiseb River has been considered the approximate northern boundary of the Tsondab Sandstone (Marker, 1977; Ollier, 1977; Besler and Marker, 1979). However, reddish-brown, consolidated arenites were noted on the southeastern flank of Swartbank Mountain and in the vicinity of Zebra Pan and Baken Kopje, thus extending the previously known northern limits of the Tsondab Sandstone to beyond the Kuiseb River (Fig. 9).

The Tsondab Sandstone was studied in outcrop chiefly on the interfluvies between the Kuiseb and Gaub Rivers, to the south of the Kuiseb below the Gaub confluence, and underlying the main Namib Sand Sea west of the monitoring area between Natab and the Delta (Fig. 9). Sub-outcrops of arenites identified here as Tsondab Sandstone are located in the proto-Kuiseb Valley trending southwestwards from the Nausgombab/Chausib area down the regional slope towards the Barrowberg/Gomkaeb vicinity (Fig. 9). Much of the Tsondab Sandstone west of about Harubes has similarly been designated as sub-outcrop (Fig. 9) because the arenites are commonly overlain by lag gravels of the Karpfenkliff Formation in that area.

As mentioned earlier, the lower boundary of the Tsondab Sandstone is formed by the NUS. Within the proto-Kuiseb and -Gaub Valleys, the upper boundary of the Tsondab Formation is demarcated by the Karpfenkliff Conglomerate, whereas on the interfluvies, the consolidated reddish-brown arenites are commonly capped by the Kamberg Calcrete. In the western sector, the Tsondab Sandstone is overlain by Karpfenkliff lag gravels or exhibits a bevelled but uncalcreted surface (Fig. B.1).

The maximum thickness of Tsondab Sandstone exposed in the study area is 70 m, but, at this locality near the Kamberg, the basal contact is not exposed. Thicknesses of 40 - 50 m were noted in some cliff sections of the cemented arenites that crop out in the proto-Kuiseb Valley. To the west, in the vicinity of the granite outcrop in the sand sea to the south of Swartbank (Fig. 9), thicknesses of some 40 - 60 m were deduced for the bevelled Tsondab Sandstone from seismic investigations undertaken by Van Zijl (1970).

These values for the thickness of the Tsondab Sandstone are less than those reported from other localities in the Namib Desert. At Tsondab Vlei, the type locality, the prominent reddish sandstone cliffs are some 60 - 90 m high. Barnard (1973) reported a maximum thickness of c. 220 m for Tsondab Sandstone from a borehole drilled on the farm Dieprivier along the eastern edge of the Namib to the south of the study area. Besler and Marker (1979) recorded thicknesses ranging from 45 - 200 m for their Namib Sandstone (= Tsondab Sandstone) but many of these are minimum values only because the basal contacts are rarely exposed.

### 2.2.3 Lithology and structure

The Tsondab Formation consists mainly of reddish quartzose sandstone that is, in places, cemented by carbonate (Ollier, 1977; Besler and Marker, 1979; SACS, 1980). However, other lithotypes are included in the six facies constituting the Tsondab Formation in the study area. Salient features of the six facies are summarised in Table 3 and simplified reference sections have been included on the distribution map (Fig. 9).

#### Facies A: Gomkaeb Basal Breccia Member

These rudaceous deposits, up to 3 m thick, are composed mainly of angular to sub-angular, rarely subrounded, vein quartz clasts cemented in a matrix of quartz chips, angular sand-sized grains and mica flakes (Fig. 8; reference sections GM, KC, and CC in Fig. 9; Fig. 10). Most clasts are pebble- to cobble-sized. Sub-rounded granule- to pebble-sized garnet grains are a common constituent of the finer-grained sections of the Gomkaeb Basal Breccia.

Calcium carbonate is the most common cement, but, in places, minor amounts of dolomite were also recorded. Internal stratification is apparently lacking and clast imbrication was not observed. The basal breccia grades upwards into the locally-restricted, rudaceous Facies B in the Gomkaeb-

TABLE 3: Summary of the six principal facies constituting the Tsondab Sandstone Formation within the study area.

FACIES	LITHOLOGIC DESCRIPTION	NOTES
F CARBONATE	greyish, whitish; indurated; mainly dolomite.	<ul style="list-style-type: none"> <li>• ZEBRA PAN CARBONATE MEMBER: reference section KP (Fig. 9)</li> <li>• Maximum thickness c. 3 m</li> <li>• Scattered, locally-restricted distinctive occurrences interbedded in Facies C and D or resting directly on Late Precambrian bedrock.</li> <li>• Gypsum casts, trackways and burrows; vegetation casts.</li> </ul>
E QUARTZ ARENITE	whitish, greyish, reddish-brown, commonly mottled; cemented by carbonate; mica flakes and garnets minor but conspicuous.	<ul style="list-style-type: none"> <li>• Reference sections CC and KC (Fig. 9).</li> <li>• Maximum thickness c. 50 m</li> <li>• Infills shallow, wide bedrock depression of proto-Kuiseb Valley.</li> <li>• Pedotubules common in cliff sections.</li> </ul>
D QUARTZ ARENITE	reddish-brown; cemented by carbonate and gypsum.	<ul style="list-style-type: none"> <li>• Reference section S0 (Fig. 9).</li> <li>• Up to c. 45 m thick.</li> <li>• Restricted area south of Kuiseb and west of Harubes; distribution coincides with that of Karpfenkliff lag gravels.</li> <li>• Large-scale macro-fractures and patterned ground.</li> <li>• Reworked, cemented variation of Facies C?</li> </ul>
C QUARTZ ARENITE	reddish-brown; consolidated but only patchily cemented by carbonate.	<ul style="list-style-type: none"> <li>• Reference section KM (Fig. 9).</li> <li>• At least up to 70 m thick.</li> <li>• Interflues south and north of proto-Kuiseb Valley as well as in western area.</li> <li>• Massive to stratified, including large-scale, steeply-dipping cross-beds.</li> <li>• Territana-like biogenic structures cross-cutting internal stratification.</li> <li>• Characteristic unit of Tsondab Sandstone Formation (<i>sensu</i> SACS, 1980).</li> </ul>
B QUARTZ BRECCIA – CONGLOMERATE	buff to mottled reddish-brown and whitish; carbonate-cemented; garnets abundant and mica flakes common.	<ul style="list-style-type: none"> <li>• Reference section GM (Fig. 9).</li> <li>• Maximum thickness c. 10 m.</li> <li>• Locally developed in Gomkaeb-Harubes area.</li> <li>• Predominantly massive, minor horizontal layers of coarser quartz clasts and rare cross-stratification; clasts angular to sub-rounded.</li> </ul>
A QUARTZ BASAL BRECCIA	whitish to reddish-brown, carbonate-cemented; garnets, quartz grit, and mica flakes common constituents of matrix.	<ul style="list-style-type: none"> <li>• GOMKAEB BASAL BRECCIA MEMBER: reference sections, CC, KC, GM (Fig. 9).</li> <li>• Maximum thickness c. 3 m.</li> <li>• Rests on Namib Unconformity Surface; prominently developed on schistose Kuiseb Formation of the Late Precambrian Damara Sequence; absent or poorly-formed over planed-off granites intrusive into Damara Sequence.</li> <li>• Massive, poorly sorted; angular to rarely sub-rounded quartz and garnet clasts; locally derived from the underlying bedrock.</li> </ul>

Harubes area (Fig. 9, reference section GM) and into Facies E sandstone in the proto-Kuiseb depression between Nausgomab/Chausib and about Gomkaeb (Fig. 9, reference sections CC and KC). The base of the typical Tsondab reddish arenite (Facies C and D) is rarely exposed in the study area.

#### Facies B

This facies comprises breccia-conglomerate, up to 10 m thick, in the Gomkaeb-Harubes area (Fig. 9, reference section GM). These deposits are lithologically similar to the Gomkaeb Basal Breccia and consist chiefly of pebble-sized, angular to sub-rounded vein quartz clasts cemented by calcite and dolomite in a matrix of angular, coarse sand-sized quartz and small garnet grains. Layers of coarser pebble- to cobble-sized quartz clasts, interbedded in the finer breccia-conglomerate, are commonly horizontally disposed and laterally extensive but, at some places, rare cross-stratification is seen (Fig. 11).

#### Facies C and D (typical Tsondab Sandstone)

These arenites consist mainly of fine to medium sand-sized quartz grains that are commonly coated by orange to reddish-brown iron oxides. The sand grains are, to some degree, rounded and grain shape varies from well-rounded to sub-angular, similar to that noted in the modern dune sands (Ward and Von Brunn, 1985b). The reddish-brown arenites of Facies C are predominantly consolidated and only patchily cemented (Fig. 9, reference section KM), whereas those of Facies D are usually cemented by carbonate (Fig. 9, reference section SO). Gypsum has also been noted in the matrix of Facies D sandstone where it forms small lenses (Besler, 1972; Watson, 1980).

In the Facies C arenites, large-scale, steeply-dipping cross-stratification was observed at a number of outcrops across the width of the study area (Fig. 12). These structures are particularly well-preserved in the western part of the study area, e.g., south-west of J-line interdune valley (Figs. 9; 12a). The foresets dip predominantly in a northerly to north-easterly direction, but rare reversals in this trend were noted. Large-scale horizontal to low-angle stratification was also recorded but, at many exposures, Facies C sandstones appear massive. In places, local unconformities are evident in the consolidated reddish-brown arenite (Fig. 12b). Tubular and spheroidal structures, closely resembling modern termitaria structures, were noted in many Facies C outcrops (Fig. 13) and commonly are sites of patchy calcium carbonate precipitation.

Patterned ground features, including polygons up to 20 m in diameter and large-scale macro-fractures (Fig. 14), are characteristic for areas underlain by the carbonate-cemented sandstones of Facies D. The polygons, recognised by Besler (1972), Goudie (1972), Ollier and Seely (1977), and Watson (1980), appear to be related to the large-scale macro-fractures which are 30 - 150 m wide and can be traced individually over several kilometres. The macro-fractures, commonly infilled with loose dune sands, inter-sect at oblique angles and form curved, in places almost circular, patterns on the surface of the Facies D sandstone. Significantly, the distribution of Facies D arenites coincides closely with that of lag gravels and thin conglomerates of the Karpfenkliff Formation west of Harubes. In the western sector, south of the granite outcrop (Fig. 9), a thin, horizontally-lying Facies D sandstone rests on strongly cross-bedded arenite typical of Facies C (Fig. 15).

#### Facies E

These carbonate-cemented arenites are composed chiefly of angular to sub-rounded quartz grains; mica flakes are a minor but conspicuous component as are local concentrations of sand- to granule-sized garnet grains (Fig. 9, reference sections CC and KC). Calcite and dolomite, in varying proportions, are the principal cementing materials. The arenaceous sediments comprising Facies E include both unstained sand grains and some coated with an iron oxide patina. The presence or absence of a patina on the sand grains generally gives rise to a mottled, reddish versus greyish appearance to the cliff exposures of the Facies E sandstone. In turn, a general pattern in colour distribution in this sandstone was commonly noted in the cliff exposures, from a whitish arenite under the upper contact through a mottled zone to a more uniform reddish- to greyish-brown colour in the basal portions (Fig. 16).

The sediments of Facies E are situated in the proto-Kuiseb bedrock depression that trends south-westwards from the Nausgomab/Chausib area, near the base of the Escarpment, to about the Barrowberg/Gomkaeb vicinity (Fig. 9). A lateral change in the sedimentary character of Facies E was detected down the regional slope away from the Escarpment. In the proximal reach, above the Kuiseb-Gaub confluence, the arenites are chiefly massive and contain thin horizons, mostly less than 0.2 m thick, of rounded pebbles (Fig. 9, reference section CC; Fig. 16), whereas farther downslope, at the Kamberg Cliff, a well-layered, thinly-bedded succession of greyish arenites alternating with uncemented reddish-brown arenites and thin dolomite horizons is exposed (Fig. 9; Fig. 17). Internal sedimentary structures appear to be lacking in the cemented arenites of Facies E. Pedotubules, commonly associated with the mottled arenite zones, are evident as positive relief structures in many of the cliff exposures (Fig. 18).

#### Facies F: Zebra Pan Carbonate Member

This non-arenaceous facies is made up of locally-restricted, indurated carbonate deposits designated the Zebra Pan Carbonate Member of the Tsondab Formation (Figs. 8; 9, reference section KP). The scattered exposures of the Zebra Pan Carbonate cap, or are interbedded in, arenites of Facies C and E (Fig. 19). The carbonate outcrops which form small mesas on Late Precambrian bedrock to the north of the Kuiseb (Fig. 9) have also been included in this facies. The dominant sediment type is a whitish to greyish, fine-grained, hard carbonate. At the type locality, dolomite is the principal carbonate but minor amounts of calcium carbonate were detected in several beds (Fig. 8).

The Zebra Pan Carbonate is massive to finely-laminated and some outcrops display at least several distinct, thin beds (Fig. 8). Wedge-shaped casts, 0.03 - 0.05 m long, were noted on the surface of several beds at the type outcrop (Fig. 20) and probably contained gypsum crystals (Von Brunn, Hobday and van Dijk, pers. comm., 1981). Trackways and burrows, some infilled with reddish-brown sand, were also recorded at the type locality, as was a wavy layer of vesicular carbonate resembling a fine algal network that has been replaced by dolomite.

##### *2.2.4 Mode of origin*

The Tsondab Sandstone, which crops out over a large portion of the Southern and Central Namib, is attributed to dune and sand sheet accumulation under desert conditions (Martin, 1950, 1957, reprinted 1974, p. 69-78; Selby, 1976; Ol-

lier, 1977; Besler and Marker, 1979; SACS, 1980; Ward *et al.*, 1983). However, the recognition of at least six facies in the Tsondab Formation within the Kuiseb Valley west of the Escarpment implies a more complex history of sediment accumulation.

#### Facies A: Gomkaeb Basal Breccia Member

This unit is developed prominently on the planed, quartz-mica schists of the Kuiseb Formation (Late Precambrian Damara Sequence). The constituent quartz clasts are poorly rounded and are derived from quartz clasts are cutting the underlying Kuiseb Formation schist. The garnets can similarly be matched with those of the underlying schistose bedrock, a correlation that was also noted by Ollier (1977). Significantly, the metagraywackes and metapelites of the Kuiseb Formation, which underlie a considerable portion of the Kuiseb River drainage system (Fig. 2), are cut by numerous quartz veins and, in places, are garnetiferous.

These observations, as well as the minor thickness (up to 3 m) of the Gomkaeb Breccia, indicate that these deposits are former regoliths or lithosols on the NUS which originated prior to the accumulation of the Tsondab Sandstone. Some support for this interpretation was obtained from a comparison of the Gomkaeb Basal Breccia with the modern skeletal soils developed on the Kuiseb Formation metasediments in the Khomas Hochland (Fig. 21).

#### Facies B

These deposits contain abundant, poorly-rounded quartz clasts which indicate limited transport and abrasion. Although lithologically similar to the Gomkaeb Basal Breccia, the rare cross-bedded strata exposed at some places suggest deposition by fluvial processes (Harms *et al.*, 1975). The breccia-conglomerate is, therefore, interpreted as reworked colluvium, deposited in a small alluvial fan derived from the topographic high of the Barrowberg. The Damaran metasediments comprising the Barrowberg are markedly garnetiferous and, significantly, the Facies B breccia-conglomerate also contains abundant garnet grains.

However, the terrestrial origin for the NUS and overlying Gomkaeb Basal Breccia, which grades upwards into a predominantly arenaceous sequence, was questioned by McCarthy (pers. comm., 1983) and some members of the SASQUA 1983 post-conference tour. McCarthy and others suggested that such a sequence could also reflect a regressive shoreline succession, the sea water thus providing the source of carbonate cement. This contention is countered by several observations:

- (i) The NUS extends into embayments in the Great Escarpment at c. 1 000 m altitude which is considerably higher than the c. 170 m.a.s.l. recorded as the upper level of transgressive marine sediments on the Atlantic coast in the Buntfeldschuh - Bogenfels area (Stocken, 1978).
- (ii) The Great Escarpment was formed by headward erosion following the break-up of West Gondwana and the coastal tract bevelled by pediplanation processes (Martin, 1973; Dingle and Scrutton, 1974).
- (iii) The vein quartz clasts and garnet grains in the Gomkaeb Basal Breccia are locally-derived and do not reflect the redistribution or the rounding generally resulting from marine action (Ollier, 1977). Moreover, if the Gomkaeb Basal Breccia represented a regressive marine gravel, the basal conglomerate/breccia should also have been developed on the planed Salem and Donkerhuk granites

in the western sector of the study area. In addition, no marine fossils have been found in these basal deposits.

- (iv) The carbonate cement could easily come from a terrestrial source, being derived from the calcareous metasediments of the Late Precambrian Damara Sequence exposed in the Kuiseb drainage system, particularly the marble and limestone in the Gaub Valley, e.g., the Tinkeringheib (Fig. B.1). South of the study area, the Escarpment is formed by the limestones and dolomites of the Naukluft Nappe Complex (Geological map of SWA/Namibia, 1980). The prevailing wind regime during the accumulation of the Tsondab Sandstone was from a southerly quadrant (Ward *et al.*, 1983) which would have facilitated the introduction of aerosolic carbonate into the Kuiseb Valley.

#### Facies C

The high degree of maturity ( $\geq 90$  per cent quartz grains) of these sandstones, the ubiquitous oxidised patina on the well-rounded to sub-angular grains, and, in particular, the large-scale, steeply-dipping cross-beds preserved in the reddish-brown arenites of Facies C, lend support to the views of previous workers that the typical Tsondab Sandstone represents dune and sand sheet accumulations under desert conditions. Large-scale cross-stratification, similar to that preserved in the Tsondab Sandstone, was observed in modern dunes of the main Namib Sand Sea (Fig. 22), providing additional credibility to these interpretations. Further support for assuming a terrestrial origin for the palaeo-dunes is provided by the termitaria-like biogenic structures commonly preserved in these reddish-brown arenites.

The northerly to north-easterly dip directions noted in the dune-derived arenite confirm Barnard's (1973) observations and fall within the north-westerly to north-easterly dip directions reported by Besler and Marker (1979). McKee (1982) showed, as did field observations in this study (Fig. 22), that internal sedimentary structures of modern dunes in the Central Namib reflect the direction of contemporary winds. Accordingly, Ward *et al.* (1983) suggested that the dune-derived arenites of the Tsondab Formation were deposited under a predominantly southerly wind regime, similar to that of the present day.

#### Facies D

The paucity of internal sedimentary structures in the Facies D arenites is attributed to the diagenetic cementing of the sands and development of large-scale macro-fractures and patterned ground. Ollier and Seely (1977) linked the patterned ground to jointing in the underlying Tsondab Sandstone, whereas Besler (1972) and Watson (1980) suggested that the polygons were caused by the desiccation of gypsum-rich sediments. Watson (1980) noted that the polygons are closely associated with the large-scale macro-fractures, features he interpreted as relict fluvial channels. However, an alternative explanation is proposed for the origin of the macro-fractures.

The cementing on the Facies D arenite was probably promoted by the carbonate-bearing waters associated with the fluvial processes responsible for the deposition of the Karpfenkliff Formation gravels west of Harubes. The cementation of sediments by calcium carbonate can lead to a considerable expansion in their volume (Goudie, 1973, p. 60-63), in some cases up to c. 50 per cent (Netterberg, 1982). The macro-features, therefore, were probably formed as the result of expansion of the Tsondab Sandstone during diagenetic cementation

and are thus genetically related to the smaller-scale patterned ground polygons. The formation of the patterned ground reflects an increase in volume of the arenaceous sediments (C.J. Talbot, pers. comm., 1982) and not a volume decrease associated with desiccation as suggested by Besler (1972) and Watson (1980).

#### Facies E

The local unconformities noted at some places in the arenites of Facies C indicate periods of non-deposition, or possibly even erosion, during the accumulation of the Tsondab Formation dunes and sand sheets. The filling of the proto-Kuiseb Valley was probably promoted during these periods (Martin, pers. comm., 1981). The arenites of Facies E consist mainly of angular to sub-rounded quartz sands that closely resemble those derived from the present Kuiseb catchment (Ward, 1984a) and these deposits exhibit a lateral fining trend down the regional slope, away from the Escarpment.

This, together with the presence of mica flakes, garnets, the lack of clayey/silty material, and the absence of well-preserved internal sedimentary structures, indicates deposition in ephemeral, relatively low-energy, streams draining from the Escarpment into the bedrock depression that formed the proto-Kuiseb Valley. Martin (1950) noted that, during contemporary flood events, thin layers of pebbles and cobbles are easily worked into the sandy beds of present-day ephemeral rivers in the Namib. This observation may explain the presence of thin, scattered pebble horizons in the Facies E sandstone in the proximal area.

The pedotubules displayed on the cliff exposures of the Facies E sandstone have been interpreted as root casts recording periods when vegetation had grown in the sandy sediments that fill the proto-Kuiseb Valley (Martin, 1957 reprinted 1974, p. 69; Selby, 1976). However, some of these structures could also be diagenetic features reflecting remobilisation of the carbonate cement in joint zones. This contention is supported by the rectangular pattern commonly formed by pedotubules on the Facies E cliff sections which resembles the solution features developed in calcareous coastal aeolianites (King, 1951, p. 112; Coetzee, 1975). Furthermore, the colour change and mottling in the cliff sections is probably the result of hydromorphic processes (*sensu* MacVicar *et al.*, 1977, reprinted 1981) which were related to groundwater levels associated with the deposition of younger, Karpfenkliff fluvial sediments.

Selby (1976) suggested that the reddish, 3 m thick layers seen in the Kamberg Cliff exposures are palaeosols, reflecting suitable conditions for soil formation at intervals during the accumulation of the Facies E sandstone. However, these beds consist mainly of typical dune-derived quartz grains that are not cemented by carbonate but contain abundant salt (both halite and sylvite). Cross-stratification was observed in several exposures of these reddish beds (Fig. 23) which also contain numerous termitaria-like biogenic structures. This cross-stratification is reminiscent of that formed on the upwind side of aeolian dunes (Bigarella, 1972). These laterally-extensive, conspicuous reddish beds are interpreted as terrestrial dune sands (Facies C type), encroaching from the Tsondab sand sea on the southern interfluvium northwards into the proto-Kuiseb Valley. The Facies E deposits are thus a lateral, valley-fill equivalent of the aeolian Facies C arenites.

#### Facies F

The carbonate composition and the presence of gypsum crystal casts indicate that the Zebra Pan Carbonate originated

in pans and are therefore considered playa deposits.

The trackways, sand-filled burrows and dolomitised algal filament network reflect limited biogenic activity that is to be expected in ephemeral water bodies (pans) in a desert environment. The small mesas of Zebra Pan Carbonate studding the plains are a good example of an inverted relief - deposited originally in hollows, the carbonate is now harder than the surrounding Tsondab Sandstone or Kuiseb schist and therefore more resistant to erosion. The carbonate deposits are also, in places, included in the Tsondab Sandstone, a relationship reported from other ancient aeolian sand successions where thin, locally-restricted limestone and dolomite bodies have been interpreted as palaeo-playas (-pans) (Walker and Middleton, 1977).

#### Summary

The Tsondab Sandstone deposits accumulated in several different environments. The base of the Tsondab succession consists, over a wide area, of a regolith or lithosol comprising mainly resistant vein quartz clasts preserved as a basal breccia resting on the NUS. The lack of deep-reaching weathering in the Late Precambrian bedrock, notably the schistose Kuiseb Formation of the Damara Sequence, under the NUS (Fig. 5) is attributed to arid conditions prevailing at that time (Selby, 1977; Ollier, 1978).

That desert conditions also influenced the subsequent accumulation of the arenaceous sediments of the Tsondab Formation is evidenced by the palaeo-dune and -sand sheet deposits occurring on the interfluvium to the south, north and west of the proto-Kuiseb Valley. A prevailing southerly quadrant wind regime, similar to the present day one, is inferred from the dip directions in the Tsondab dunes. In the western sector, dune-derived arenites were influenced by later cementation processes that resulted in the formation of macro-fractures and patterned ground.

The proto-Kuiseb Valley, stretching south-westwards from the Nausgomab/Chausib area to the Barrowberg, contains mostly arenaceous sediments that were deposited by ephemeral streams draining from the Escarpment zone down the regional slope towards the Atlantic Ocean. However, this fluvial system appears not to have persisted through to the Atlantic coast but terminated amongst dunes of the ancient sand sea in the vicinity of Gomkaeb. Dunes, from a southern sand source, encroached upon the distal reach of the proto-Kuiseb Valley during this period.

During intervals of increased humidity in this early desert phase, a number of pans formed in which carbonate deposits accumulated. The pan deposits are more common in the eastern sector, suggesting an increase of annual rainfall from west to east across the Central Namib which is similar to today's pattern (Schulze, 1969; Besler, 1972). This contention is further supported by the improved preservation of large-scale cross-beds in the dune-derived arenite of the western exposures compared with those in the east.

#### 2.2.5 Age and correlation

The Tsondab Sandstone is not well-dated and Besler and Marker (1979) proposed a general "Tertiary to Recent age" for the accumulation of these arenaceous sediments. However, this estimate can be refined by an appreciation of the lower and upper boundaries of the Tsondab Formation in the Central Namib.

The NUS is considered to be of Late Cretaceous age (Martin, 1950, 1973, 1975; Ollier, 1977; Ward *et al.*, 1983). Within the proto-Kuiseb Valley, the Tsondab Sandstone is overlain by the Karpfenkliff Conglomerate which contains water-worn clasts of consolidated reddish-brown arenite and indurated Zebra

Pan Carbonate. The Karpfenkliff Conglomerate, correlated with fossiliferous deposits in the Southern and Northern Namib, is thought to be of an Early to Middle Miocene age (Martin, pers. comm., 1981; Table B.3., Appendix). The Tsondab Sandstone on the interfluvies to the south and north of the proto-Kuiseb Valley is capped by pedogenic calcretes (Kamberg Formation) which are equated with similar duricrusts in the Southern Namib to which an End Miocene age has been assigned (Stocken, 1978; pers. comm., 1983; Ward *et al.*, 1983; Table B.3., Appendix). These field relationships and proposed correlations suggest that the Tsondab Sandstone Formation accumulated during the Palaeogene.

The Gomkaeb Basal Breccia could be of Early Tertiary age because Ward *et al.* (1983) correlated these deposits with the Tafelberg Quartzites (*sensu* Stocken, 1978) of the Southern Namib. However, Stocken (pers. comm., 1983) suggested that the shallow proto-Kuiseb Valley could be of Early Tertiary age and the valley deposits of Early to Middle Miocene age, similar to the fossiliferous units in the Southern Namib. He, nevertheless, retained a Miocene age for the Karpfenkliff Conglomerate and agreed to an End Miocene age for the Kamberg Calcrete. The apparent lack of suitable datable material in the Tsondab Sandstone has, unfortunately, precluded a more accurate determination of the maximum age of this formation.

Martin (1950) equated the palaeo-dunes in the Central Namib with the aeolianites in the upper Buntfeldschuh Formation in the Southern Namib, a correlation supported by Ward *et al.* (1983). The Buntfeldschuh aeolianites, which were also deposited under a southerly wind regime, overlie Middle Eocene marine sediments and are capped by an End Miocene pedogenic calcrete (Stocken, 1978; pers. comm., 1982/83; Fig. 24a). The accumulation of extensive sandy desert deposits in the Southern and Central Namib at that time was probably facilitated by the c. 500 m drop in sea level off the south-western African coast during the Oligocene (Siesser and Dingle, 1981). This low stand in sea level would have shifted the coastline some 100 - 200 km farther westwards (Dingle *et al.*, 1983, p. 313). It is tempting to speculate that the Oligocene regression exposed extensive continental shelf areas which would have been important sources of sand for the dunes and sand sheets that accumulated in the Namib during Tsondab times.

Arenaceous deposits, similar to the Tsondab Sandstone, have been recorded elsewhere in the Namib tract (summarised in Ward *et al.*, 1983, Table B.3). In the Southern Namib, the Rooilepel Beds comprise reddish, strongly cross-bedded aeolianite deposited by southerly quadrant winds and capped by the End Miocene calcrete (Stocken, 1978; pers. comm., 1982/83). The aeolian Fiskus Beds were similarly deposited by southerly winds and lie stratigraphically above the Early Miocene Grillental beds. The fluvial Grillental Beds are, in places, underlain by aeolianite (Stocken, pers. comm., 1983). The greenish-brown aeolianites in the upper Buntfeldschuh Formation (Fig. 24a) are considered, as mentioned earlier, to be southern equivalents of the Tsondab Formation dune sands to the south of the Kuiseb.

North of the Kuiseb, carbonate-cemented, arenaceous and conglomeratic deposits fill the wide, shallow proto-Ugab Valley (Mabbutt, 1952). These sediments, capped by a prominent surface limestone (= pedogenic calcrete), resemble the carbonate-cemented Facies E sandstone filling the proto-Kuiseb Valley. Massive to cross-bedded, reddish sandstone was noted by the writer in the Kharu-gaiseb and Hunkab Valleys of the Skeleton Coast. Reddish-brown arenites, similar to the Tsondab Sandstone and up to c. 150 m thick, are exposed along the lower Kunene Valley (Beetz, 1933; Fig. 24b). In south-western Angola, reddish, unfossiliferous arenites, equated with the

Tsondab Sandstone

(Ward *et al.*, 1983; Table B.3.) are capped by the terrestrial Catrona Conglomerate which has been dated to the Early Miocene (Soares Carvalho, 1961).

It is concluded that desert conditions prevailed in the Namib in the Middle (possibly even Early) Tertiary, during which time several major arenaceous units accumulated in the narrow strip west of the Escarpment. The Tsondab Sandstone Formation, deposited in a large area of the Southern and Central Namib, is one such lithostratigraphical unit. The proto-Kuiseb Valley in the Central Namib was filled initially by a mainly arenaceous suite of sediments. This forerunner of the Kuiseb drainage system was bounded to the south, west and north by desert dunes and sand sheets - a situation that persisted through much of the Palaeogene and today is exemplified by the Tsauchab and Tsondab Rivers that terminate amongst dunes of the Namib Sand Sea without reaching the Atlantic Ocean.

## 2.3 Karpfenkliff Conglomerate Formation

### 2.3.1 General

The Tsondab Formation arenites in the proto-Kuiseb Valley are overlain by carbonate-cemented rudaceous deposits, a relationship first recognised by Martin (1950, 1957 reprinted 1974, p. 68, 153) and subsequently by Ollier (1977, 1978) and Besler (1980). Ollier (1977, 1978) reported that the Tsondab Sandstone had been eroded by a fossil westerly directed drainage system and he referred to the resultant erosion bevel as the Tsondab Planation Surface (Table 1). High-lying conglomerates were shown together with the Tsondab Sandstone as Tertiary deposits on the 1980 Geological map of S.W.A./Namibia (Fig. 2). In this study, these rudaceous deposits overlying the Tsondab arenites have been named the Karpfenkliff Conglomerate Formation (Table 2; Fig. B.1).

Thick conglomerates, similar to those in the Kuiseb Valley, were also observed in the Gaub Valley. These exposures, together with the thin conglomerates and lag gravels exposed mainly in the interdune areas of the western sector, have been included in the Karpfenkliff Formation (Fig. B.1). The name is derived from Martin and Korn's first shelter, Carp Cliff (English translation), where these high-lying conglomerates occur within the Kuiseb Valley (Martin, 1957, reprinted 1974).

Carp Cliff, a mesa situated near the bridge across the Kuiseb Canyon (23°20'S; 15°45'E), is the type locality of the Karpfenkliff Conglomerate Formation (Figs. 25, 26). The type section is displayed in Figure 26. Although the Karpfenkliff Conglomerate comprises chiefly rounded to well-rounded clasts, comparatively minor exposures of rudaceous, breccia-like deposits are considered lateral equivalents of the conglomerate. These locally-restricted rudites are informally referred to as the Koedoe River breccia. A reference locality and section for this facies, which in places may be a breccia-conglomerate, is also shown on the type locality map (Fig. 26; 23°19'S; 23°52'E).

### 2.3.2 Distribution and thickness

Calcified gravels, resting on elevated terraces adjacent to the Kuiseb and Gaub Rivers, were traced from near the base of the Escarpment down the axes of the proto-Kuiseb and -Gaub Valleys to about Gomkaeb (Fig. 25). West of Gomkaeb, the Karpfenkliff Formation is developed mainly as thin conglomerates or, more commonly, as lag gravels exposed in the interdune valleys (Fig. 25). At Natab, the lag gravels and thin conglomerates of the Karpfenkliff Formation persist west- to west-north-westwards under the modern sand sea whereas

the Kuiseb River flows north-westwards from that point.

The Koedoe River breccia is exposed in close proximity to topographic highs, such as inselbergs and prominent ranges of resistant hills (Figs. B.1, 25), including Swartbank Mountain (23°20'S; 14°50'E), Kamberg (23°35'S; 15°45'E), Saagberg (23°43'S; 15°50'E), and Tinkeringheib (23°35'S; 15°55'E).

Near the base of the Escarpment, the Karpfenkliff Conglomerate rests on bevelled bedrock or the basal portion of the Tsondab Formation. This relationship suggests that there was no incision into the bedrock by the fluvial processes ultimately responsible for the deposition of the Karpfenkliff sediments. Farther downslope, the Karpfenkliff Conglomerate transgresses over the valley-fill arenites of the Tsondab Formation in the proto-Kuiseb Valley (longitudinal profile, Fig. 25). West of Harubes, lag gravels and thin conglomerates rest on Tsondab Sandstone that exhibits patterned ground features. The upper boundary of the Karpfenkliff Conglomerate is demarcated, in the eastern sector, by pedogenic calcretes (Yaalon and Ward, 1982). These duricrusts (Kamberg Calcrete Formation) have developed in the uppermost several metres of the Karpfenkliff deposits and their location closely marks the former land surface (Yaalon and Ward, 1982). The boundary relationships of the Karpfenkliff Conglomerate are illustrated in Fig. 27 which provides an oblique aerial view down the proto-Kuiseb Valley south-west of Carp Cliff.

In the proximal area, the Karpfenkliff Conglomerate is 40 - 60 m thick in the Kuiseb Valley and some 40 m thick in the upper Gaub Valley (Fig. 28). The Karpfenkliff Conglomerate wedges out away from the base of the Escarpment and is 20 - 30 m thick in the Carp Cliff - Kamberg Cliff sector, and thins markedly to c. 5 m in the Gomkaeb area, about 100 km from the Atlantic coast (longitudinal profile, Fig. 25). West of Harubes, the Karpfenkliff deposits are chiefly lag gravels and poorly-defined conglomerate less than 4 m thick that cap, in the western, distal sector, low topographic highs of Tsondab Sandstone exposed in the interdune valleys. Fluvially-derived gravels from the Tsondab drainage system, lying south of the Kuiseb River, were deposited at a later stage amongst these distal Karpfenkliff gravels (Figs. B.1; 25).

### 2.3.3 Lithology and structure

Where typically developed, the Karpfenkliff Formation consists of carbonate-cemented conglomerates. The mostly rounded to well-rounded clasts, usually scarred by abundant percussion marks, are set in a matrix of fine to medium sand-sized, angular to sub-rounded quartz grains. Upslope from Gomkaeb (Fig. 25), lenses and flat-lying beds of quartz arenite, usually less than 2 m thick, are intercalated with the rudaceous deposits. The arenaceous sediments are also cemented by carbonate, chiefly calcite. Mica flakes and sand to granule-sized garnet grains are minor, but conspicuous, components of the conglomerate matrix and arenite beds. Clayey and silty material is rare in the Karpfenkliff Conglomerate.

Amongst the clasts of the Karpfenkliff Formation, three rock types are prevalent; these are also characteristic for all rudaceous successions in the Kuiseb drainage system, viz.:-

- (i) metaquartzites, derived chiefly from the Late Precambrian Damara Sequence (Fig. 29a) and, to a lesser extent, the Rehoboth Sequence in the Gaub Valley. The Damaran metaquartzites are commonly greyish to brownish and fine-grained.

- (ii) vein quartz, derived mainly from the numerous quartz veins that cross-cut the metasediments of the Damara Sequence (Fig. 29b). These clasts, typically opaque to whitish, are the most abundant type in the pebble/small cobble size range.
- (iii) quartzite (silicified sandstone), derived from the Etjo Formation (Jurassic age) that forms the high-lying relict cappings on the Klein Gamsberg and Gamsberg (Fig. 29c). The Etjo quartzites are reddish or greyish and the component quartz grains are plainly visible. Some Etjo clasts are conspicuously pitted (Fig. 29c), a feature attributed in part to the weathering out of gypsum crystals contained in the host rock.

Other important, but altogether subordinate, clast types in the Karpfenkliff Conglomerate include:-

- (i) marble, derived from the Damara Sequence exposures in both the Kuiseb and Gaub Valleys, near the base of the Escarpment. These clasts are up to large boulder size in the proximal Karpfenkliff Conglomerate exposures, but are minor components farther downslope.
- (ii) Reddish-brown arenite clasts (Tsondab Sandstone) and whitish indurated carbonate clasts (Zebra Pan Carbonate) form a distinctive 1 - 2 m thick bed that is laterally extensive for over 100 m in the western extremity of the Kamberg Cliff (Fig. 30). Rounded, greyish sandstone clasts, derived from the Tsondab Formation Facies E, are scattered through the Karpfenkliff Conglomerate succession in the exposures between Carp Cliff and Gomkaeb. Rare clasts of fine-grained breccia-conglomerate, typical of the Tsondab Formation Facies B, were noted in the distal exposures.

Maximum clast size decreases from proximal to distal reach, a trend that coincides with the downslope wedging-out of these rudaceous deposits (longitudinal profile, Fig. 25). Boulder-cobble conglomerates prevail in the proximal exposures in both the Gaub and Kuiseb Valleys (Figs. 28a, 31; Table 4). The size and abundance of boulders in the exposures of the Kamberg Cliff area are considerably reduced compared with that in the proximal reach outcrops (Fig. 25; Table 4). In the Gomkaeb vicinity, the Karpfenkliff Conglomerate comprises mainly cobble- and pebble-sized clasts (Fig. 25; Table 4), whereas farther westwards, the distal sediments are characterised by thin, pebble-cobble gravels.

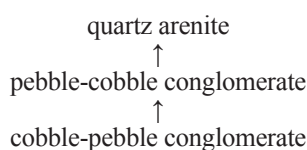
TABLE 4: Summary of maximum clast size measurements (quartzite clasts only) for the Karpfenkliff Conglomerate Formation.

n = 10; S.D. = Standard Deviation.

LOCALITY	a (max.) mm	b (interm.) mm	c (min.) mm
Sphinx R., Schlesien S.D.	954 106	603 124	472 119
Carp Cliff S.D.	661 103	326 54	280 39
Kamberg Cliff S.D.	429 63	265 51	207 48
Gomkaeb S.D.	191 26	126 28	91 17

The Karpfenkliff Conglomerate commonly displays an upward-fining trend in exposures between the proximal area and the Kamberg Cliff. The basal contact is demarcated mainly by a boulder-cobble conglomerate that grades upwards into cobble- or pebble-dominated rudaceous sediments (Fig. 26).

In the Escarpment - Kamberg Cliff sector, the Karpfenkliff Conglomerate is massive to crudely horizontally-stratified (Figs. 28a; 32a). At several localities, rare cross-stratified cobble-pebble conglomerates were noted (Fig. 32b). In places, horizontally-stratified conglomerates are interbedded with 0,3 - 2 m thick, flat-lying, apparently massive arenite layers (Fig. 32a) some of which can be followed laterally for up to 50 m. At some localities, wedges of predominantly finer-grained (cobble-pebble) conglomerate interdigitate with lenses of arenite. In addition, small-scale (< 1 m thick) upward-fining units of:



were noted in both horizontally- and cross-stratified conglomerate exposures of the Karpfenkliff Formation (Fig. 33). These units are commonly repeated in a rhythmic pattern.

The larger clasts in some of the proximal- to mid-reach Karpfenkliff Conglomerate exposures are imbricated, with their long (a-) axes transverse to, and their intermediate (b-) axes dipping into, the palaeo-current direction.

In the Gomkaeb area, Karpfenkliff Conglomerates are mostly less than 5 m thick and commonly include hardpan and honeycomb structures that reflect pedogenic calcrete formation (Yaalon and Ward, 1982). Consequently, primary sedimentary structures have been destroyed at that locality. West of Harubes, the Karpfenkliff lag gravels and thin conglomerates (< 4 m thick) reflect limited pedogenic calcretisation. The resistant clasts in the distal exposures are commonly highly polished from a "desert varnish" (Selley, 1976, p. 8; Ollier, 1977), the development of which has probably been promoted by the current Namib Desert environment.

#### Koedoe River breccia

These deposits consist of angular to sub-rounded clasts (Fig. 34), contrasting with rounded clasts typical of the Karpfenkliff Conglomerate (Fig. 29). The clast composition in this facies can be closely matched to the bedrock lithology of the local topographic highs adjacent to the Koedoe River breccia exposures.

#### 2.3.4 Mode of origin

##### Conglomerate

The alluvial character of the Karpfenkliff Conglomerate was appreciated by Martin (1950, 1957, reprinted 1974, p. 69) and Ollier (1977). This rudaceous formation provides the earliest record of a well-developed Kuiseb-Gaub drainage system in the Central Namib. The deposition of the Karpfenkliff Conglomerate on sandstones of the Tsondab Formation implies a change from arid desert climate to more mesic conditions in the Central Namib - Escarpment region. This contention is supported by the Koedoe River breccia deposits which transgress over dune-derived Tsondab Sandstones abutting local topographic highs within the Central Namib.

The eastern limit of the Karpfenkliff Conglomerate is situated at about the same longitude in both the Kuiseb and Gaub Valleys, suggesting that the Escarpment was less dissected, and possibly farther west, than at present (Figs. B.1, 25). The

principal clast types were derived from the Escarpment zone. A broad unidirectional flow pattern, confirmed by the decrease in maximum clast size away from the source area, was detected in the Karpfenkliff Conglomerate when this was mapped down a regional slope from near the base of the Escarpment towards the Atlantic Ocean. These observations corroborate the alluvial origin of this formation and mitigate against a marine one. Additional support for the alluvial deposition of the Karpfenkliff Formation is provided by the transverse imbrication of larger clasts, a pattern that has been reported from a number of fluvial settings and is formed once clasts roll on a river bed (Harms *et al.*, 1975; Reineck and Singh, 1975, p. 126; Blatt *et al.*, 1980, p. 123).

The bulk of the Karpfenkliff Conglomerate was deposited in the broad, shallow proto-Kuiseb and -Gaub Valleys. No significant incision into the Late Precambrian bedrock underlying the Namib Unconformity Surface was observed in the proximal reach. This apparently unconfined depositional pattern displayed by the Karpfenkliff Conglomerate, the distribution of these rudaceous deposits relative to the Escarpment and the downslope wedging-out of the sediment wedge are characteristics noted elsewhere in alluvial fan environments (McGowen and Groat, 1971; Bull, 1972; Cooke and Warren, 1973, p. 173; Selley, 1976, p. 257-259; McGowen, 1979; Blatt *et al.*, 1980, p. 629-632; Reading, 1980, p. 15-20, 42-45). These workers also recorded a decreasing clast size from proximal to distal reach on alluvial fans. The development of alluvial fans is commonly associated with braided stream sedimentation (Bull, 1972; Miall, 1977a, b). Field observations indicate that similar conditions prevailed during deposition of the Karpfenkliff sediments.

The Karpfenkliff Conglomerate commonly exhibits crude horizontal stratification in which the larger clasts are transversely imbricated, an arrangement similar to that described from modern, braided gravel stream environments (Doeglas, 1962; are, 1964; Smith, 1974; Boothroyd and Ashley, 1975; Hein and Walker, 1977). These workers suggested that gravel sheets and longitudinal bars are characterised by massive to crudely horizontally-stratified rudaceous deposits containing imbricate pebbles orientated transverse to river flow. Eynon and Walker (1974) attributed crude horizontal stratification and imbrication of pebbles, preserved in Pleistocene deposits, to sheetflood transport of gravels in shallow ephemeral braided channels and over low-relief bars. Additional support for a gravelly braided stream palaeo-environment is provided by the rare exposures of cross-stratified Karpfenkliff Conglomerate in the Carp Cliff - Kamberg Cliff areas that resemble the inclined foresets preserved in transverse gravel bars (Harms *et al.*, 1975; Hein and Walker, 1977). The cross-bedded units in the Karpfenkliff Conglomerate were noted downslope from the proximal reach which is dominated by massive to crudely horizontally-stratified conglomerate, a relationship also observed in several modern gravelly braided rivers (Hein and Walker, 1977; Reading, 1980, p. 25). The lack of clayey and silty material in the Karpfenkliff Formation is comparable to that in modern alluvial fan-gravelly braided stream environments (Bull, 1972; Selley, 1976, p. 264), thus providing additional support for this palaeo-environmental interpretation.

The sand-sized grains comprising much of the Karpfenkliff Conglomerate matrix were probably deposited by settling and infiltration processes during waning flow conditions, similar to those noted in contemporary braided streams (are, 1964; Smith, 1974). The bimodality of an Early Palaeozoic conglomerate, comprising boulders in a coarse sandstone matrix setting, was attributed by Hobday and Von Brunn (1979) to strong current activity followed by a reduction in flow that al-



lowed the suspended sand-sized grains to settle into the interstices of a coarse bedload gravel. Simons *et al.* (1979) noted a similar bimodality in contemporary ephemeral streams of arid areas. The small-scale horizontally- and cross-stratified, upward-fining units in the Karpfenkliff Conglomerate reflect decreasing current velocities during depositional phases. Repetition of flood surges during the deposition of the Karpfenkliff gravels is implied from the rhythmically-stacked sequences of these upward-fining units.

Crude horizontal stratification and transverse clast imbrication in rudaceous sediments is indicative of upper flow regime (Harms *et al.*, 1975; Blatt *et al.*, 1980, p. 640). The occurrence of these features in the proximal and mid-reach exposures of the Karpfenkliff Conglomerate implies relatively high fluvial energy conditions during deposition. This contention is supported by the high degree of rounding and abundance of arcuate percussion scars (Schumm and Stevens, 1973) exhibited by the resistant clast types of the Karpfenkliff Conglomerate. Such conditions were caused by a considerable increase in the discharge and run-off from the Escarpment and interior plateau catchment areas. The downslope-thinning clastic wedge of the Karpfenkliff Conglomerate thus reflects the generation of an alluvial fan system by sedimentation in gravelly braided rivers that drained into the broad proto-Kuiseb and -Gaub Valleys from the upland areas and developed across the Central Namib tract. Relatively high discharge was probably due to a substantially increased, but nevertheless seasonal, rainfall in the catchment area.

The Karpfenkliff Conglomerate thus records a major fluvial episode in the Central Namib tract. Palaeo-environmental conditions were, however, probably not as humid as those prevalent in the modern alluvial fan system of the Kosi River in India (Gole and Chitale, 1966; McGowen, 1979) and the carbonate cementation of the Karpfenkliff Conglomerate indicates predominantly semi-arid conditions at that time in the Central Namib - Escarpment region. Partridge (1982) suggested that epeirogenic uplift of the subcontinent in Middle Tertiary times initiated fluvial deposition off the west coast of southern Africa. Stocken (pers. comm., 1983) however, cited field evidence from the Southern Namib, notably the Grillental Beds, Gemboktal Beds and Arries Drift Gravels, that indicates a comparatively humid, but semi-arid, environment at that time. Mesic conditions within the Central Namib tract are also inferred from the bevelled but uncemented, dune arenites of the Tsondab Formation which are exposed in the western sector of the study area.

#### Koedoe River breccia

The angular nature of the constituent clasts and the proximity of these breccia deposits close to topographic highs indicates that sediment has hardly been transported. Therefore, the Koedoe River breccia is interpreted as redistributed scree/talus material deposited in small alluvial fans or, in some places, as sieve deposits (*sensu* Bull, 1972). Short periods of relatively high rainfall during Karpfenkliff times are likely to have generated the rapid run-off from local topographic highs which was responsible for the emplacement of the Koedoe River deposits.

#### Cementation

The Karpfenkliff Formation deposits have been cemented mostly by calcite, but, in places, dolomite was also recorded. Cementation was probably effected by  $\text{CaCO}_3$  precipitation from groundwaters that fluctuated in the sediment pile (Yaalon and Ward, 1982). The calcification of thick gravel deposits in the Vaal Valley, South Africa, has been attributed to a

fluctuating, but steadily dropping, water table under semi-arid conditions (Netterberg, 1969). Glennie (1970) noted that wadi (wash) gravels in arid zone ephemeral streams can be cemented relatively rapidly by calcium carbonate precipitated out of evaporating floodwaters. Marbles and limestones of the Late Precambrian Damara Sequence (mainly Corona Formation) are particularly well exposed in the Gaub Valley towards the base of the Escarpment. The Gomab River Formation marbles crop out in the Kuiseb Valley, notably between the Sphinx and Chausib Rivers and to the south-west of the Kamberg. Large boulder-sized carbonate clasts, derived from these outcrops, were recorded in the proximal Karpfenkliff Conglomerate deposits. The thin alluvial fans which extend north-westwards from the Tinkeringheib towards the Gaub River are composed chiefly of whitish marble clasts. These bedrock exposures and calcareous clasts are the probable source of carbonate responsible for the cementing of the Karpfenkliff Formation deposits.

The calcification of the Karpfenkliff gravels appears to have, in places, promoted the matrix-supported character of the rudaceous deposits by the expansion in volume associated with this diagenetic process (Goudie, 1973, p. 60-63; Netterberg, 1982). The apparent lack of sedimentary structures in the sandy interbeds of the Karpfenkliff Conglomerate is also attributed to cementation by carbonate as are the apparent slump structures, which resemble internal buckling in some conglomeratic layers. Thus original sedimentary structures in the Karpfenkliff deposits have been considerably modified by diagenetic calcification and concomitant volume expansion of the rudaceous and interbedded arenaceous units.

#### 2.3.5 Age and correlation

The Karpfenkliff Conglomerate rests upon, and is therefore younger than, the Tsondab Sandstone Formation of presumed Middle Tertiary age. The Kamberg Calcrete Formation, developed in the uppermost several metres of the Karpfenkliff Conglomerate, is a palaeosol formation of supposedly End Miocene age (Stocken, 1978, pers. comm., 1982/83; Ward *et al.*, 1983). Accordingly, deposition of the Karpfenkliff sediments seems to have taken place in the Miocene. This estimate is also based upon correlation with similar deposits of Early to Middle Miocene age in the Namib (Martin, pers. comm., 1981; Ward *et al.*, 1983; Table B.3).

Deposits in the Southern Namib which are correlated with the Karpfenkliff Conglomerate include the Arries Drift Gravel Formation, a fluvial aggradation succession up to 80 m thick in the Lower Orange Valley which contains a rich vertebrate fossil fauna of Middle Miocene age (Corvinus and Hendey, 1978; Stocken, 1978; SACS, 1980; Fig. 35). Vertebrate fossils in the Grillental Beds of the Elizabeth Bay Formation, cropping out in the Sperrgebiet between Lüderitz and the Orange River, date these fluvio-lacustrine deposits to the Early Miocene (Greenman, 1969; Stocken, 1978; SACS, 1980). The high-lying conglomerate terraces of the Lower Khan and Swakop Rivers, to the north of the Kuiseb, are situated in a stratigraphically similar position to the Karpfenkliff Conglomerate and were considered to be of an Early Miocene age by Gevers (1936).

Farther north, the uppermost parts of the carbonate-cemented deposits filling the Middle Ugab Valley (Mabbutt, 1952) have been correlated with the Karpfenkliff Conglomerate (Ward *et al.*, 1983; Table B. 3). In the Northern Namib (Angolan sector), the Catrona Conglomerate overlies reddish, unfossiliferous arenites and has been dated as Early Miocene (Soares Carvalho, 1961). This field relationship is reminiscent of that in the Central Namib where the Karpfenkliff

Conglomerate overlies the Tsondab Sandstone.

These tentative correlations, therefore, indicate that fluvial conditions prevailed in the Namib tract and adjacent Escarpment and upland areas during the Early to Middle Miocene and was probably a consequence of relatively high, seasonal rainfall in the catchment areas following the arid desert conditions in the Early to Middle Tertiary. In the Central Namib, the terrestrial Karpfenkliff Conglomerate records the initial manifestation of a well-established proto-Kuiseb/Gaub drainage system that is attributed to this Early to Middle Miocene fluvial phase. The aggradation of thick, fluvially-deposited gravels in the Lower Orange River (Arries Drift Gravel Formation) is linked to a high stand (c. 30-40 m) of sea level during the Miocene (Stocken, 1978; Hendey, 1981; Stocken and Campbell, 1982). Although a similar relationship could not be established in the case of the Karpfenkliff Conglomerate, the Rooikop gravels exposed in the extreme north-western sector of the study area (Fig. B.1) may, in part, be coastal equivalents and are discussed briefly in the following section.

## 2.4 Rooikop Gravels

### 2.4.1 General

Gypsiferous, oyster-bearing sandy to conglomeratic deposits are poorly exposed in the extreme north-western sector of the study area near Walvis Bay (Fig. B.1). These fossiliferous sediments, exposed mainly in man-made trenches and surface scrape-pits, are equated with similar deposits on the north side of the Walvis Bay - Rooikop road that have been described by Miller and Seely (1976) and recognised as an informal unit, the Rooikop gravels, by SACS (1980) (23°00'S; 14°36'E).

### 2.4.2 Distribution and thickness

Rooikop gravels are restricted to the extreme north-western sector of the study area between the Walvis Bay-Rooikop road and the Quarries bedrock ridge (Figs. B.1, 36). Scattered exposures were recorded from about 17 to 40 m above sea level.

Poorly exposed, the deposits overlie reddish Damaran granites as well as cemented grits and arenites of Tertiary age. The Rooikop gravels are covered by a gypsum crust similar to that formed on the plains north of the Kuiseb River and west of Gobabeb (Fig. B.1). A lag of locally-derived granitic grus covers the gypsum crust in the north-western sector, thus further obscuring the Rooikop gravels.

Estimations of the thickness of the Rooikop gravels in the study area were hindered by the disturbed condition of the exposures. Thicknesses of 0,5 - 2 m appear to be average values, which are similar to those of 1 - 1,6 m reported for the Rooikop gravels in trench exposures only a few kilometres to the north (Miller and Seely, 1976; Fig. 36). Relationships between the Rooikop gravels and other Cenozoic deposits in the Kuiseb Valley were not established in the field.

### 2.4.3 Lithology and structure

The deposits consist chiefly of gravel, sand and oyster (*Striostrea margaritacea*) shells (Fig. 37), together with other unidentified shells, set in a matrix of pinkish-brown gypsum. Cobbles and pebbles were noted in the limited exposures of the study area and farther north, beyond the Walvis Bay - Rooikop road, several gypsum-cemented gravel beds were recorded by Miller and Seely (1976). The observations of Miller and Seely (1976) are pertinent for a further apprecia-

tion of the Rooikop gravels because of the limited exposure and disturbed nature of these deposits in the study area.

In the trench exposure north of the study area, the Rooikop gravels are composed principally of unconsolidated to gypsum-cemented arenite intercalated with cobble-pebble gypsum-cemented gravels and greenish, clayey beds (Miller and Seely, 1976). All fossiliferous layers, 0,04 - 0,45 m thick, are conglomeratic. The deposits are mainly horizontally-stratified and individual beds could be traced over considerable distances; lenses of cross-stratified sands are locally present (Miller and Seely, 1976).

### 2.4.4 Mode of origin

The presence of numerous *S. margaritacea* shells in the gypsiferous sediments restricted to the coastal zone points towards a littoral depositional environment. The occurrence of robust oyster shells implies warmer sea water conditions than those experienced today under the present cold-water upwelling system of the Benguela Current (Haughton, 1931; Carrington and Kensley, 1969; Dingle *et al.*, 1983, p. 282).

Miller and Seely (1976) proposed that the Rooikop gravels are fluvio-marine deposits, the clasts having been swept by sheet-flooding of the proto-Swakop River into a partially sheltered coastal embayment or tidal lagoon. The terrestrial sediments were then reworked by coastal marine and aeolian processes into beach deposits that are today preserved 20-40 m above sea level (Miller and Seely, 1976; Rust and Wieneke, 1976; SACS, 1980). The presence, however, of Etjo quartzite clasts in the Rooikop gravels suggests that the Kuiseb drainage system also contributed a significant amount of rudaceous material to the coast at that time. The horizontally-layered, laterally-persistent conglomerate beds resemble the fossil beach deposits D, E and F in the Southern Namib which also contain a warm-water littoral fauna (Stocken, 1978; Stocken and Campbell, 1982; Fig. 38).

The Quarries bedrock ridge (Fig. 36) may have formed the approximate southern boundary of the coastal embayment proposed by Miller and Seely (1976). Thus, the low bedrock scarp demarcating the eastern limit of the Kuiseb Delta between Quarries and Haob/Mile 16 (Fig. 36) could be the cliff-cut shoreline related to a high stand of sea level that was ultimately responsible for the deposition of the Rooikop gravels.

### 2.4.5 Age and correlation

The Rooikop gravels, although fossiliferous, are not as yet satisfactorily dated. Several <sup>14</sup>C dates, ranging from about 30 000 to 35 000 Bp, were obtained by Rust and Wieneke (1976) but, as pointed out by SACS (1980), these values should be treated with caution because of possible contamination. Oyster-bearing conglomeratic deposits have been recorded from coastal, high-lying beach deposits in the Namaqualand and the Sperrgebiet sectors of the Southern Namib (Haughton, 1931; Carrington and Kensley, 1969; Stocken, 1978). These deposits were previously assigned a Pleistocene age but recently Hendey (1981), Stocken and Campbell (1982) and Stocken (pers. comm.) have postulated an earlier, possibly Miocene, age for those littoral deposits containing a fossil warm-water fauna.

Stocken and co-workers recognised six beach deposits in the Sperrgebiet, of which the upper three, designated D, E and F (highest and oldest), carry a warm-water fauna and the lower three, called A, Band C, are characterised by a modern, cold-water fauna (Stocken and Campbell, 1982). The full es-

establishment of a cold-water upwelling system associated with the Benguela Current is dated to the Late Miocene (Siesser, 1978, 1980). Therefore, Stocken and Campbell (1982) reasoned that the deposits containing a warm-water fossil fauna pre-date the development of the cold-water Benguela System and, on the basis of fossil estuarine worm casts in the Arries Drift Gravels at c.40 m above sea level, proposed a Miocene age for beaches D, E and F (also Stocken, pers. comm., 1982/83). Marine deposits, characterised by a fossil warm-water fauna, also provide evidence of a transgression in the south-western Angola sector of the Namib during the Miocene (Soares Carvalho, 1961).

The Rooikop gravels and a +26m oyster deposit at Cape Cross, c.140 km farther north, are tentatively correlated with the "30-m gravels" in the Southern Namib by SACS (1980, p. 609). It is possible, therefore, that the Rooikop gravels record at least one high sea level stand in the Central Namib during the Miocene, which accords with a similar events elsewhere in southern Africa at that time (Hendey, 1981; Siesser and Dingle, 1981).

Recently, however, Pether (1986) has identified three marine units lying higher than 12 metres above sea level at Hondeklip Bay, Namaqualand. He recognised sedimentary packages with transgressive maxima at 30 m, 50 m and 90 m above sea level. The 30 m and 50 m packages are characterised by the zone fossils, *Donax rogersi* and *D. haughtoni*, respectively (Pether, 1986). Pether and the writer found *D. rogersi* in Rooikop gravels between 15-30 m above sea level (Pether, 1986) and we noted the presence of marine deposits at a maximum elevation of 50 m, as well as the existence of older, phosphatised sediments at elevations around 30 m above sea level. The Rooikop gravels are thus a composite sedimentary unit, consisting of several marine packages that require further attention to unravel their apparently complex history.

## 2.5 Kamberg Calcrete Formation

### 2.5.1 General

Calcrete duricrusts commonly form resistant cappings on the land surface in the eastern sector of the study area. The calcretes are well developed on the Karpfenkliff Conglomerate in the proto-Kuiseb and -Gaub Valleys as well as on the Tsondab Sandstone on the interfluves of this palaeo-drainage system (Figs. 27, 39). The calcretes formed on a land surface prior to the canyon incision by the Kuiseb drainage system west of the Escarpment, a relationship first perceived by Martin (1950, 1957, reprinted 1974, p. 153) and subsequently noted by Ollier (1977, 1978) and Yaalon and Ward (1982). The calcretes, as appreciated by these earlier workers, provide an important stratigraphic marker in the Cenozoic succession of the Central Namib.

The thin, but distinctive, lithological unit formed by the duricrusts is established here as the Kamberg Calcrete Formation. The type locality is the calcrete-capped mesa of Tsondab Sandstone occurring a few kilometres south-west of the Kamberg at about 23°36,5'S and 15°39'E (Figs. 39, 40). The type section was described originally by Yaalon and Ward (1982) and is included here with additional information on the composition of the calcrete duricrust (Fig. 40).

### 2.5.2 Distribution and thickness

The Kamberg Calcrete commonly caps the Tsondab Sandstone and Karpfenkliff Conglomerate east of about Homeb. Thus the distribution of the calcrete coincides closely with that of these two older formations and only the occurrences

in the Ubib basin south-east of Tinkeringheib are shown separately (Fig. B.1).

The lower contact of the Kamberg Calcrete is gradational into sediments comprising the underlying, older formations. The upper surface is either exposed (Figs. 27, 39) or is covered by unconsolidated sands. The upper boundary of the Kamberg Calcrete is thus marked by a geomorphological event, notably the canyon incision by the Kuiseb drainage system west of the Escarpment.

The maximum thickness recorded for a Kamberg Calcrete profile, which is best developed in Tsondab Sandstone, is c. 5 m (Yaalon and Ward, 1982; Fig. 40). However, the most conspicuous layer of the Kamberg Calcrete is the resistant hardpan horizon which varies from 1 - 3 m thick.

### 2.5.3 Lithology and structure

The Kamberg Calcrete results from accumulation of calcium carbonate in a relatively narrow, horizontal zone within a host material. Where the Kamberg Calcrete caps the Tsondab Sandstone, the duricrust is composed of calcium carbonate and detrital quartz sand grains, the amount of which varies in vertical profile (Fig. 40). Water-worn clasts are incorporated in the Kamberg Calcrete profiles developed on the Karpfenkliff Conglomerate. The calcrete profiles are better developed on the fine-grained Tsondab Formation sediments than on the coarse-grained Karpfenkliff Conglomerate because these latter sediments are commonly well-cemented by carbonate which tends to obscure the profile sequence of the Kamberg Calcrete.

A horizon sequence is recognised in vertical profile through the thick duricrusts of the Kamberg Calcrete, a situation best observed in the consolidated, reddish-brown arenites of the Tsondab Formation (Figs. 40, 41). A well-developed calcrete profile, from the surface downwards, consists of:

- laminar crust/rind; up to 0,05 m thick;
- hardpan calcrete; c. 2 m thick;
- honeycomb calcrete; c. 1 m thick;
- nodular calcrete; c. 2 m thick;
- gradational
- host material

(after Yaalon and Ward, 1982)

The Kamberg Calcrete commonly exhibits small-scale, low amplitude pseudo-anticline and -syncline structures that are particularly evident in profiles east of about Gomkaeb (Figs. 42, B.1).

### 2.5.4 Mode of origin

The horizon sequence in vertical profile and the relatively thick, up to 0,05 m, laminar crust capping the hardpan calcrete (Fig. 43), is considered proof of the pedogenic origin of the Kamberg Calcrete (Yaalon and Ward, 1982).

The Kamberg Calcrete developed on the interfluves and plains of an earlier landscape prior to canyon incision by the Kuiseb drainage system west of the Escarpment. The formation of such thick pedogenic calcretes, particularly on the relatively carbonate-free, reddish-brown quartz arenites of the Tsondab Formation, required a considerable period of land-form stability. Yaalon and Ward (1982) suggested that this period would have been in the order of at least several hundreds of thousands of years, during which time climatic conditions were semi-arid, with a seasonal annual rainfall of about 350 - 450 mm. The lack of Kamberg Calcretes in the western part of the study area suggests that the rainfall pattern at that time followed a westward-diminishing trend similar to that displayed today (Schulze, 1969; Besler, 1972).

Netterberg (1978) noted that a calcrete profile may not necessarily be formed during a discrete event and that carbonate may still be active within the profile. Nevertheless, in arid to extremely arid environments, such as the Namib Desert, a complete calcrete profile may constitute a fossil feature (Netterberg, 1978). The Kamberg Calcrete, because it is exposed, is a fossil feature in the arid Central Namib, thus confirming its importance as a palaeo-environmental indicator and a stratigraphic marker in the Cenozoic succession of the Kuiseb Valley. The presence of small-scale pseudo-anticlines and -synclines in the Kamberg Calcrete testifies to the high degree of maturity of these duricrusts. These structures are a consequence of the internal buckling of a duricrust from the expansion in volume associated with pedogenic calcretization and, in other regions, have only been reported from mature calcrete profiles (Netterberg, 1969, 1980; Reeves, 1970; Goudie, 1973, p. 60-63; Watts, 1977).

The Kamberg Calcrete forms several different duricrust levels in the landscape. Although these relatively flat-lying surfaces are, in places, stepped, the Kamberg Calcrete at several localities also covers gentle slopes between higher and lower duricrust-capped levels (Figs. 19, 44). The development, therefore, of the Kamberg Calcretes in the study area was not synchronous, a deduction borne out by the calcretes situated on the western side of the Kamberg. At that locality, an incipient pedogenic calcrete capping the Tsondab Sandstone was eroded and reworked during the deposition of a sedimentary breccia of the Koedoe type (Karpfenkliff Formation) which itself exhibits a well-formed calcrete duricrust. Similarly, Blümel (1976, 1979, 1982) recognised three calcrete-capped levels on Tsondab Sandstone in the Ubib drainage basin (Fig. B.1). Nevertheless, the Kamberg Calcrete formed prior to the canyon incision by the Kuiseb drainage system west of the Escarpment.

The Tsondab Sandstone on the interfluvies in the Central Namib comprises mainly consolidated quartz arenites that contain minor, locally-restricted patches of carbonate-cemented sand grains. The formation of thick calcrete duricrusts in this relatively sterile, predominantly dune-derived arenite implies an external origin for the calcium carbonate. The limestones and dolomites of the Naukluft Mountains, as well as the Damaran marbles near the base of the Escarpment are the probable original source of carbonate for the Central Namib area. The carbonate could have been introduced down the proto-Kuiseb and -Gaub Valleys by the fluvial processes responsible for the deposition of the Karpfenkliff gravels and subsequently redistributed as calcareous dust by aeolian action.

The contemporary Tsondab River, which drains the Naukluft Mountains consisting mainly of limestones and dolomites, provides a modern analogue for this proposed mechanism. Dunes of the main Namib Sand Sea block the lower reaches of the Tsondab River, which forms a terminal pan (playa) at its endpoint (Fig. 3).

Calcareous dust is commonly blown out of the Tsondab River bed and terminal pans by strong south-westerly and north-easterly winds (Fig. 45). The entrained fines are then transported in suspension over the present day dunes.

During the formation of the Kamberg Calcrete, the specific environmental conditions prevalent at that time would have promoted the deposition of aeolian-transported calcareous dust and the subsequent accumulation of calcium carbonate in the uppermost part of the land surface. The associated pedogenic processes, best developed in the unconsolidated surficial cover, were ultimately responsible for the formation of the

Kamberg Calcrete duricrusts in the Central Namib.

Blümel (1982), in following Yaalon (pers. comm., 1981), also proposed an aeolian origin for the calcium carbonate in the calcrete duricrusts of the Ubib/Cha-re area but he postulated two alternative sources:-

(i) a coastal area whereby marine-derived carbonate, particularly during periods of lowered sea level during the Pleistocene, was transported inland as dust by southwesterly winds;

(ii) the Etosha Pan of northern S.W.A./Namibia, which provided calcareous dust to high-level wind systems that transported this material to the Central Namib.

However, the writer favours the derivation from local source areas and the comparatively simple mechanism outlined earlier for the origin of the calcium carbonate incorporated in the Kamberg Calcrete.

#### 2.5.5 Age and correlation

The Kamberg Calcrete post-dates the deposition of the Tsondab and Karpfenkliff sediments and pre-dates the canyon incision by the Kuiseb drainage system west of the Escarpment (Fig. B.1, Table 2). An Early to Middle Miocene age has been proposed for the Karpfenkliff Conglomerate (section 2.3.5) and the deep incision by the westward-draining rivers occurred near the end of the Tertiary (Martin, 1950, 1961; Korn and Martin, 1957). Therefore, the author believes that the Kamberg Calcrete originated towards the end of the Miocene, an age which is also based on a correlation with similar pedogenic calcretes in the Southern Namib (Stocken, 1978, pers. comm. 1982; SACS, 1980; Fig. 46; Table B.3).

Pedogenic calcretes, dated stratigraphically as End Miocene, cap the aeolianites of the upper Buntfeldschuh Formation (Fig. 24a) and Rooilepel Beds, as well as the Gemsboktal Gravels, in the Southern Namib. Stocken (1978; pers. comm. 1982/83) considered these calcretes in the Southern Namib to be important stratigraphic markers in the Cenozoic succession and confirmed the similarity between these duricrusts and the Kamberg Calcrete in the Central Namib.

Calcrete duricrusts of a corresponding setting have also been noted in the Northern Namib. The 70-100m thick surficial deposits in the Middle Ugab Valley are capped by a pedogenic calcrete (= surface limestone of Mabbutt, 1952). Farther north, the Cenozoic deposits that partly fill the Sechomib, Munutum and Engo Valleys also display a similar pedogenic calcrete duricrust (Ward *et al.*, 1983).

The Kamberg Calcrete constitutes the Central Namib equivalent of an important Cenozoic stratigraphic marker that developed over a large section of the Namib Desert during the Late Tertiary. The formation of thick calcretes represents a relatively long period of landform stability, probably some 500 000 years, in the Late Miocene during which time semi-arid, seasonal rainfall conditions suitable for calcrete pedogenesis prevailed over much of the Namib.

The duricrusts of the Kamberg Formation have not been destroyed by dissolution which suggests that the subsequent climates of the Central Namib have not been humid for any prolonged period (Yaalon and Ward, 1982). Predominantly desert conditions are thus inferred for the Central Namib region since the end of the Miocene, which accords well with the Late Cenozoic age postulated for the current aridity in the Namib Desert (Korn and Martin, 1957; Soares Carvalho, 1961; Siesser, 1978, 1980; Endrödy-Younga, 1978; Tankard and Rogers, 1978; Ward *et al.*, 1983).

## 2.6 Oswater Conglomerate Formation

### 2.6.1 General

Following the widespread development of the Kamberg Calcrete Formation, the Kuiseb drainage system west of the Escarpment incised through the Tertiary surficial cover (comprising the Tsondab, Karpfenkliff and Kamberg Formations) into the Late Precambrian bedrock (Fig. 6). Subsequently, the Kuiseb River and its major tributaries experienced several aggradational/erosional phases, the first of which is recorded by a suite of calcified, predominantly rudaceous sediments that are preserved mainly as terrace deposits (Fig. 47).

These terrace deposits, with upper surfaces lying between c. 30 m and c. 70 m above the present river beds, were recognised by Martin (1950), Korn and Martin (1957), De Waal (1966), Scholz (1968) and later reported on by Goudie (1972), Rust and Wieneke (1974, 1980), Sawyer (1976), Marker (1977), Ollier (1977, 1978) and Ward (1982). Many of these earlier workers used ambiguous names, e.g., “40 m terrace”, “30 m cliff” and “calcrete cliff” in their discussions of terrace deposits in the Kuiseb Valley. Sawyer (1976), in his provisional legend for the geological maps 2315CA Gobabeb and 2315CB Gorob, called these terrace deposits “Unit 36, Oswater 1”, whereas Ollier (1977) used the term “Ossewater Conglomerate”. Ward (1982), in the absence of a formal name, referred to the calcified sediments as the “Ossewater” -type conglomerates. The name, Oswater Conglomerate Formation, is established here for these deposits. The geographical name is derived from the Topnaar village, *Gomagu-Ilgams*, c. 19 km upstream from Gobabeb, which can be translated as either “Oswater” or “Ossewater” (Ward and Van Wyk, 1985). The former spelling has been adopted (Ward, 1984b).

The mesa formed by cemented gravels c. 4 km downstream from the Oswater village, and situated on the north (right) bank of the Kuiseb River, is the type locality for the Oswater Formation. This locality, at about 23°38'S and 15°08'E, is shown in Figure 48. The type section is sited on the downstream-facing edge of this conglomerate mesa which carries the Water Affairs beacon, DW306 (Fig. 48).

### 2.6.2 Distribution and thickness

Outcrops of Oswater Conglomerate were traced along the Kuiseb River from about the Uspass Bridge, near the base of the Escarpment, downstream to Gobabeb (Fig. 49). The occurrence of small Oswater exposures between Natab and Gobabeb extend the previous downstream limits, set at Natab (Ward, 1982), by about 10 km. Similar terraces covered by calcified gravels were recorded in the lower reaches of the Kraaipoot, Nausgomab, Donkersan, Chausib and Gaub Rivers (Fig. 49). The low-lying, conglomeratic terrace deposits in the Sphinx, Witberg and Ubib watercourses are also included in the Oswater Formation.

The Oswater Conglomerate rests unconformably on the Late Precambrian bedrock (Fig. 47). A geomorphological event, viz., the canyon incision by the Kuiseb drainage system, reflects the lower boundary of the Oswater Conglomerate (Table 1). Therefore this formation post-dates the pedogenic Kamberg Calcrete, as testified by the presence of rounded hardpan calcrete pebbles and cobbles in the Oswater clast assemblage (Fig. 50). Similarly, the upper boundary originates from a geomorphological event, viz., the re-incision by the Kuiseb drainage system after the aggradation and cementation of the Oswater Conglomerate. In the canyon reach, the Kuiseb River re-incised to c. 50 m below the base of the Oswater Conglomerate thereby preserving, at a few localities,

the course of this early Kuiseb River during Oswater times (Fig. 51). In the lower reaches of the Kuiseb canyon, the Homeb Silts abut onto, and therefore post-date, the Oswater Conglomerate Formation.

The position of the Oswater exposures relative to the present Kuiseb River, as well as the pre-incision surface, is shown by the longitudinal profile in Figure 49. The general trend of increasing outcrop thickness away from the Escarpment is clearly illustrated on this profile. The Oswater Conglomerate is about 5 - 6 m thick near the base of the Escarpment and some 30 - 40 m thick in the canyon reach of the Kuiseb River. Downstream from Homeb, the base of the Oswater Conglomerate is concealed and the measured thicknesses of 20 - 30 m represent minimum values only (Fig. 49). This general westward- (downslope-) thickening trend of the Oswater Conglomerate (Fig. 49) is opposite to that of the Karpfenkliff Conglomerate (Fig. 25).

### 2.6.3 Lithology and structure

The Oswater Formation consists mainly of rudaceous and intercalated, subordinate arenaceous sediments that are well cemented by calcium carbonate. The clasts are commonly supported in an arenaceous matrix of angular to sub-rounded quartz grains. Mica flakes are a minor but conspicuous component of both the conglomerate matrix and many of the quartz arenite beds. Rare layers of calcified silt, up to several metres thick, were noted only at the type locality and at one exposure below Carp Cliff in the canyon reach (Fig. 49).

Within the Oswater Conglomerate clast assemblage, the resistant rock types characteristic of the Kuiseb drainage system, notably Damaran metaquartzites and vein quartz as well as Etjo quartzite (Fig. 29), prevail. The clasts incorporated in the Oswater Conglomerate exposures downstream from the Kuiseb - Chausib confluence (Fig. 49) were derived chiefly from the high-lying Karpfenkliff Conglomerate Formation during the incision by the Kuiseb drainage system (Marker, 1977; Rust and Wieneke, 1980; Ward, 1982). These are, therefore, typically rounded to well-rounded and commonly scarred with crescentic percussion marks. The Oswater clast assemblage also includes rare cobbles and pebbles of Kamberg Calcrete (Fig. 50). Large schist slabs and sub-angular vein quartz fragments, derived from Damaran metasediments exposed in the near vicinity, are commonly incorporated in the Oswater exposures in the canyon reach of the Kuiseb River (Fig. 52).

Maximum clast size in the Oswater Formation decreases down the Kuiseb Valley away from the Escarpment (longitudinal profile, Fig. 49; Table 5). The large boulders contained in the Oswater Conglomerate above the Kuiseb - Chausib confluence are mostly Damaran metaquartzites whereas, farther downslope, vein quartz and Etjo quartzites complement this rock type.

Two types of arenite are interbedded in the conglomeratic sediments of the Oswater Formation:

- (i) the more common arenite type is composed of angular to sub-rounded, unstained quartz grains and minor amounts of mica; these are well cemented by calcium carbonate to form resistant lenses and flat-lying beds (Fig. 52).
- (ii) the subordinate type consists of arenite wedges, up to 14 m thick, composed of well-rounded to sub-angular, iron oxide-coated quartz grains cemented by calcium carbonate. These wedges, characterised by large-scale, high-angle cross-stratification (Fig. 53), are intercalated in rudaceous deposits in the Oswater exposures along the south (left) bank of the Kuiseb River in the lower canyon - upper valley reach (Fig. 49).

TABLE 5: Summary of maximum clast size measurements (quartzite clasts only) for the Oswater Conglomerate Formation.

n = 10; S.D. = Standard Deviation

LOCALITY	a (max.) mm	b (interm.) mm	c (min.) mm
Uspass Bridge S.D.	860 138	630 116	349 128
Aros-Kuiseb confluence S.D.	915 108	515 77	426 69
Nausgomab-Kuiseb confl.; S.D.	540 61	321 66	232 51
WA 135 beacon S.D.	472 79	274 50	185 49
DW 248 beacon S.D.	448 48	325 56	222 54
Gomkaeb S.D.	448 67	262 33	203 35
WA 273A beacon S.D.	490 79	244 23	190 29
Dawataraes (c. 5 km above Homeb); S.D.	344 41	221 35	142 25
Oswater (DW 304/B beacon); S.D.	280 19	147 22	115 26
Natab S.D.	242 28	156 33	111 28

A facies change is recognised in the Oswater Conglomerate Formation over the length of its distribution in the Kuiseb Valley (Ward, 1982). Three principal zones are distinguished (adapted from Ward, 1982):

- (i) proximal reach, from the Escarpment to the Nausgomab - Kuiseb confluence;
- (ii) mid reach, from the Nausgomab - Kuiseb confluence downstream to about Aub, thus incorporating the deep canyon reach;
- (iii) distal reach, from about Aub to Gobabeb, including the lower canyon - upper valley sector of the Kuiseb River.

The distribution of the three main zones is shown in Fig. 54, which also displays reference sections for the proximal, mid and distal reaches of the Oswater Conglomerate Formation within the Kuiseb Valley.

Salient features of the three zones recognised in the Oswater Conglomerate Formation are outlined below.

#### (i) Proximal reach

The Oswater conglomerate in this zone is dominated by large boulder-sized metaquartzite clasts commonly supported in a matrix of angular to sub-rounded quartz and mica grains (Fig. 55). These proximal rudaceous deposits are massive or crudely horizontally-stratified and, in places, the large sub-rounded boulders exhibit a rudimentary transverse imbrication (Fig. 54). Intercalated arenite beds are rare in the proximal reach exposures (Fig. 54).

#### (ii) Mid reach

Rounded to well-rounded cobbles and small boulders, typical of the Kuiseb drainage system, characterise the essentially flat-lying Oswater Conglomerate beds in the mid reach exposures (Fig. 54, 56). The resistant clasts, inherited mostly from the Karpfenkliff Conglomerate, are well cemented by calcium carbonate into both matrix- and clast-supported conglomerates (Fig. 56). The conglomeratic deposits commonly form flat-lying units intercalated with subordinate but conspicuous arenite beds that are also horizontally disposed (Figs. 52, 56). As noted earlier, locally-derived Damaran schist fragments are particularly abundant in the Kuiseb canyon exposures which correspond to the mid reach zone.

The flat-lying arenite units form prominent, indurated beds up to 2 m thick that can be traced laterally over distances of 10 - 50 m. Angular to sub-rounded, fine to coarse sand-sized quartz grains and mica flakes (minor amounts) compose these arenaceous beds that are commonly bounded by thin pebble-cobble units. In many Oswater exposures, the upper surface of the arenaceous beds is marked by a veneer of coarse sand-sized quartz grains and pebble-cobble clasts. Internal sedimentary structures are usually absent but faint horizontal stratification is evident in some beds. Surface weathering of the exposed arenite layers has produced solution features that resemble "rillenkarren" described from Damaran marbles in the western part of the study area (Goudie, 1972; Sweeting and Lancaster, 1982).

#### (iii) Distal reach

Predominantly clast-supported, cobble-pebble conglomerates interdigitate with lenses of quartzose arenite in the distal reach exposures of the Oswater Formation (Fig. 57). The conglomeratic units are commonly wedge-shaped and unstratified although flat-lying beds, which apparently lack internal structures, were noted in several outcrops. At a few localities, cobble-pebble conglomerates display a low-angle stratification that consists of several upward-fining units (Fig. 58). Interbedded arenite lenses, up to 3 m thick and 50 m wide, cross-cut rudaceous and arenaceous units forming large-scale channel-like structures (Fig. 59). These arenite lenses display channel-fill cross-stratification (*sensu* Reineck and Singh, 1975, p. 91), which may be asymmetrically or symmetrically orientated (Figs. 59, 60). Other arenite beds exposed in the distal reach exhibit either horizontal stratification or appear massive. Wedges of high-angle, cross-stratified quartz arenite (Fig. 53), intercalated in south (left) bank Oswater exposures, are restricted to the distal reach of the Oswater Conglomerate distribution (Figs. 49, 54).

#### 2.6.4 Mode of origin

Many of the earlier workers, in particular Martin (1950), Korn and Martin (1957), Rust and Wieneke (1974, 1980), Marker (1977) and Ollier (1977), favoured a fluvial origin for the Oswater Conglomerate, an interpretation supported by this study.

Although the rudaceous, and most of the arenaceous, sediments making up the Oswater Formation were deposited by fluvial processes, the distinctive cross-stratified arenite wedges interbedded in south (left) bank distal zone exposures (Figs. 53, 54) are aeolian desert dune accumulations (Ward, 1982). The terrestrial character of these interbedded dune deposits is further confirmed by the termitaria-like biogenic structures cutting cross-bedded strata (Ward, 1982) and the presence of calcified pedotubules that closely resemble the roots of the extant, endemic cucurbit, *Acanthosicyos horrida* Welw. ex

Benth. & Hooker fil. Today these cucurbits (known locally as Inara) colonise and form low dune hummocks along the margin of the Lower Kuiseb River and in the interdune valleys adjacent to the river course, where their occurrence is apparently dependent on river-derived groundwater (Seely *et al.*, 1979/81). The cross-bedded strata of the dune wedges dip in a northerly direction (range: west-north-west to east-north-east) towards the early course of the Kuiseb River. This relationship is similar to that observed today where dunes from the main Namib Sand Sea enter the Lower Kuiseb Valley from a southern sand source (Ward, 1982, 1984a; Ward and Von Brunn, 1985b; Figs. 3, 61).

The intercalation of aeolian dune wedges in the otherwise conglomeratic sediments is a consequence of extensive aggradation in the early Kuiseb River (Martin, pers. comm., 1980). The preservation of the early Kuiseb River course under Oswater Conglomerate at several localities (Fig. 51) also testifies to this aggradation and to cementation of the fluvial deposits prior to the re-incision by the Kuiseb River and its major tributaries. The Oswater Conglomerate Formation is not, therefore, a residual lag accumulation on terraces cut during the incision of the Kuiseb canyon as has been suggested by Rust and Wieneke (1980).

The Oswater Conglomerate exposures are located within the canyon sector of the Kuiseb River and its major tributaries, implying deposition in a confined valley system. This laterally-constrained mode of accumulation probably contributed to the downstream increase in outcrop thickness noted in the Oswater Conglomerate (Fig. 49). By contrast, the rudaceous deposits of the Karpfenkliff Conglomerate Formation wedge out away from the Escarpment (Fig. 26) because of deposition in the wide, relatively unconfined proto-Kuiseb Valley. Although the Oswater Conglomerate inherited the majority of its resistant clasts from the Karpfenkliff Conglomerate (Marker, 1977, Ollier, 1977, Ward, 1982) these younger deposits contain larger clasts than the equivalent exposures of Karpfenkliff Conglomerate at, and downstream from, Gombaeb (Figs. 26, 49; Tables 4, 5). This difference in maximum clast size distribution is attributed to the deposition of the Oswater sediments within a confined, canyon fluvial system.

The occurrence of scattered Oswater Conglomerate outcrops between Natab and Gobabeb (Figs. 48, 49) implies that the general north-westerly course of the Lower Kuiseb River had been attained prior to the deposition of the Oswater gravels. The change in valley orientation from westerly to north-westerly in the incised Lower Kuiseb River coincides with a fundamental change in the composition and structure of the underlying Late Precambrian bedrock. Upstream from Natab, the bedrock comprises schistose metapelites and metagreywackes of the Kuiseb Formation (Damara Sequence), whereas Salem and Donkerhuk granites (associated with the Damara Sequence) are exposed in the Kuiseb valley to the west of Natab (Fig. 2; Geological map of SWA/Namibia 1980). The more resistant nature of these granites, compared with that of the schistose metasediments, appears to have inhibited deep canyon incision in the Lower Kuiseb River west of Natab. The shallow valley configuration in this lower reach may thus have facilitated a north-westerly shift in the Kuiseb River under the influence of a northward encroachment by dunes from an early sand sea lying to the south.

There are indications that a braided-fluvial environment prevailed within the Kuiseb Valley and those of its major tributaries during the accumulation of the Oswater gravels. The Oswater Conglomerate is commonly massive to crudely horizontally stratified, reminiscent of similar structures reported from modern gravelly braided stream by, amongst others,

Ore (1964), Smith (1974), Harms *et al.* (1975), and Hein and Walker (1977). The low-angle inclined stratification noted in several conglomeratic units in the distal Oswater exposures resembles that developed on margins of diagonal gravel bars or in diffuse gravel sheets in modern proximal braided stream environments (Harms *et al.*, 1975; Hein and Walker, 1977). These workers (cited above), as well as Doeglas (1962), noted that clasts contained in gravel bars of modern braided streams are commonly imbricated transverse to the river flow. A similar orientation of the large clasts was observed in the Oswater Conglomerate. The interdigitating conglomerate-arenite layers in the distal Oswater exposures reflect rapid spatial and temporal changes of erosional and depositional conditions that occur in contemporary braided streams (Doeglas, 1962; Ore, 1964). Clayey and silty material is commonly absent from braided fluvial environments (Selley, 1976; p. 264) and, significantly, these fine-grained sediments are also virtually absent from the Oswater Conglomerate Formation.

Braided fluvial systems, the formation of which is governed principally by markedly fluctuating discharge rates and high sediment loads, are developed in, amongst several other environments, semi-arid to arid regions (Doeglas, 1962; Miall, 1977a). The occurrence of aeolianite, derived from a southern sand source, within left bank exposures of Oswater Conglomerate in the lower canyon-upper valley sector of the Kuiseb River, suggests a predominantly arid environment within the Central Namib tract during the initial aggradational phase. This contention implies a degree of similarity between that early Kuiseb drainage system responsible for the deposition of the Oswater sediments and the modern river which, in its lower reaches, is flanked by dunes from the main Namib Sand Sea (Figs. 3, 61). The contemporary Kuiseb River forms a downstream-thickening and -fining wedge of unconsolidated fluvially-deposited sediment away from the Escarpment, a trend similar to that observed in the Oswater Conglomerate Formation. The modern Kuiseb River is part of an ephemeral braided-fluvial system that derives its floodwaters from summer rains in the catchment in the Escarpment and Khomas Hochland regions. Present day fluvial and aeolian processes operating in the Kuiseb River bed within the Central Namib tract produce sedimentary features that resemble some of the deposits and structures preserved in the Oswater Conglomerate. The Kuiseb River thus provides a modern analogue for a further understanding of the Oswater Conglomerate and these field observations are outlined below.

The composition of the modern sands in the present Kuiseb River, notably angular to sub-rounded quartz grains (c. 90%) and minor but conspicuous mica flakes and "heavy" constituents (Harmse, 1980; Ward, 1984a), is similar to that of the arenaceous beds in the Oswater Conglomerate. Within the mid reach zone, flat-lying, apparently massive to faintly horizontally-stratified, arenaceous beds form scattered but prominent beds intercalated in the conglomeratic layers. These beds were deposited by fluvial processes during seasonal floods and then subjected to subaerial exposure, desiccation and aeolian reworking of the sandy sediments. This contention is supported by several observations made during the course of this study.

Irregular summer floods of the modern Kuiseb River produce a variety of fluvial bedforms, including mud-draped ripples in the sandy sections, which are exposed in the bed after the ephemeral flow has terminated (Fig. 62a). These bedforms, similar to those described by Karcz (1972) from wadis in the Negev Desert, are then destroyed by desiccation and re-shaped by aeolian processes during the ensuing period of subaerial exposure (Fig. 62b). Aeolian activity during the

subsequent dry period promotes the development of a coarse sand-sized quartz grain lag by winnowing processes on the upper surface of these sandy reaches. The effects of aeolian winnowing are also pronounced in the gravelly sections of the modern Kuiseb bed, producing cobble-pebble clusters alternating with arenaceous patches (Fig. 63). These features were also noted on the upper surface of flat-lying, arenaceous beds in a number of mid reach Oswater Conglomerate exposures (Fig. 63, inset). In addition, river sands are commonly blown into the interstitial spaces between fluvially-deposited/re-worked clasts by aeolian processes during the dry periods between floods (Fig. 62). This process could explain the origin of the arenaceous matrix exhibited by much of the Oswater Conglomerate. It is also appreciated, however, that this fabric can develop by the infiltration of sand-sized grains into the interstitial spaces between clasts during waning flow conditions in braided-fluvial systems (Ore, 1964; Boothroyd and Ashley, 1975; Hobday and Von Brunn, 1979).

Groundwater through-flow and fluctuating groundwater levels were probably instrumental in cementing the rudaceous and arenaceous deposits to form the Oswater Conglomerate (Yaalon and Ward, 1982; Netterberg, 1969). The Oswater deposits are cemented by calcium carbonate and the resultant volume expansion associated with this diagenetic process may have also contributed to the matrix-supported nature of many of the conglomeratic units in this formation.

These observations, therefore, suggest that the ancestral Kuiseb was a braided, ephemerally flowing river, at least west of the Escarpment where arid conditions prevailed during the accumulation of the Oswater deposits. The occurrence of cobble-pebble conglomerates c. 30 km beyond the most downstream gravel bars in the present river bed indicates stronger river flow during the deposition of the Oswater gravels than that prevailing at present. The early Kuiseb system was, by Oswater times, draining the Escarpment zone and Khomas Hochland region of the interior plateau. Rainfall trends during the Late Cenozoic apparently resembled those experienced in S.W.A./Namibia today (Korn and Martin, 1957). Thus the Kuiseb catchment has been better-watered than the adjacent Namib Desert. It is suggested, therefore, that the deposition of the Oswater Conglomerate occurred under a more competent fluvial regime generated by a higher seasonal rainfall (probably summer) on the interior plateau.

This supposition accords well with the model, based on observations of the terraces in the Uis River, northern Central Namib, assuming progressive aridity and decreasing stream competency in the Namib tract from the Late Cenozoic to Recent (Korn and Martin, 1957). Evidence of higher discharge during the Oswater times is provided by the fluvial deposits derived from the Tsondab River drainage system to the south of the study area. These fluvial gravels, which are considered equivalents of the Oswater Conglomerate, were deposited in north-westerly to northerly streams flowing towards the open valley sector of the Lower Kuiseb River (Fig. B.1). The modern Tsondab River is blocked by dunes (Fig. 3), therefore the presence of fluvial gravels and associated Early Stone Age artefacts in the western sector of the main Namib Sand Sea reflects a more competent fluvial regime during the Early to Middle Pleistocene (Seely and Sandelowsky, 1974).

In addition, any palaeo-environmental interpretation of the Oswater Conglomerate Formation should consider that:

(i) a considerable proportion of the resistant clast types in the Oswater Conglomerate have been inherited from the Karpfenkliff Conglomerate (Marker, 1977; Ollier, 1977), therefore, clast characteristics, notably degree of rounding and presence of arcuate percussion scars, do not necessarily reflect the hydrological conditions responsible for the emplacement of the Oswater deposits (Ward, 1982);

(ii) During Oswater times, the gradient of the early Kuiseb River was steeper than that of the present course (longitudinal profile, Fig. 49). A stronger run-off and hence greater stream transport energy might then be expected in the early Kuiseb course responsible for the deposition of the Oswater gravels.

The initial incision by the Kuiseb drainage system west of the Escarpment was probably initiated by epeirogenic uplift of the subcontinent in the Late Tertiary (King, 1951, p. 193; Korn and Martin, 1957). Significantly, the Kuiseb River lies approximately along the western part of the Khomas axis, a zone of upwarping during the Tertiary (King, 1951, p. 199, 202). Subsequently, alternating aggradational and erosional phases, as well as changes in longitudinal profile, in the major river courses traversing the Namib Desert can probably be related to the climatic and eustatic fluctuations superimposed on a general progressively aridifying trend that affected this region from the end of the Tertiary (Korn and Martin, 1957; Tankard and Rogers, 1978; Tankard *et al.*, 1982, p. 453-454).

A comparable setting for the sedimentary units and structures preserved in the Oswater Formation is illustrated, on a reduced scale, in a canyon sector of the modern Kuiseb River (Fig. 64). The Kuiseb River had not flooded through this section (DW 95 beacon area) in almost two years (Fig. 64, photograph taken February 1981). Flat-lying sandy reaches (1), alternating with gravel sheets and low bars (2), were covered by a coarse sand-sized quartz grain lag. These fine- to medium-grained, sandy units were up to 0.5 m thick and rested on cobble - small boulder gravels, the interstitial spaces of which had been infilled with loose sand. These arenaceous and rudaceous units are reminiscent of similar (but lithified) features preserved in the Oswater Formation. The incorporation of schist slabs and vein quartz fragments, like in the Oswater Conglomerate (mid reach exposures in particular), is also common in the modern Kuiseb River (Fig. 64) where talus fans (3) extend down into the present river bed. Schistose bedrock (4) crops out in the modern Kuiseb River bed at numerous localities in the upper canyon reach, reminiscent of the basal contacts exposed in the Oswater Conglomerate.

In summary, therefore, the Oswater gravels and sands were deposited in an incised, ephemeral braided-fluvial system west of the Escarpment under a more effective hydrological regime than that experienced today by the Kuiseb River. Desert conditions prevailed in the Central Namib tract during the initial aggradational event in the Kuiseb drainage system. The aeolianite wedges interbedded in rudaceous deposits of the Oswater Formation provide evidence for the earliest link between the Lower Kuiseb River and dunes from a southern sand sea.

#### 2.6.5 Age and correlation

The Oswater Conglomerate records the initial aggradational phase, subsequent to the canyon incision, in the Kuiseb drainage system west of the Escarpment. The deep incision by the westward-draining rivers traversing the Namib Desert has been attributed to epeirogenic uplift of the subcontinent at the end of the Tertiary (King, 1951, p. 193; Korn and Martin, 1957). The Homeb Silts, which abut against remnants of the Oswater Conglomerate in the distal exposures, have been assigned to the Late Pleistocene (Vogel, 1982). Therefore, with suitable datable material absent, an Early to Middle Pleistocene age of the Oswater Conglomerate is assumed here. This deduction is supported by a correlation with calcified gravel terraces in the Ugab River, Northern Namib, that are similar to the Oswater Conglomerate deposits (Fig. 65). Mabbutt (1952) dated the Ugab gravels to the Early and Middle



Pleistocene because of the occurrence of ESA artefacts on the terraces.

The  $^{14}\text{C}$  dates of about 28 000 - 33 000 BP obtained for the carbonate cement in an Oswater exposure (DW 304/B) on the south side of the Kuiseb River opposite the settlement of Oswater (Vogel, 1982) warrant an explanation. Similar ages were also obtained for the hardpan calcrete on the canyon rim above the DW 304/B Oswater outcrop (Vogel, 1982). This calcrete, however, predates the earliest incision by the Kuiseb drainage system and hence is equated with the Kamberg Calcrete Formation in this study. The ages of 28 000 - 33 000 BP are about 10000 years older than the  $^{14}\text{C}$  dates of 19 000 - 23 000 BP obtained for the Homeb Silts (Vogel, 1982). The Oswater Conglomerate was cemented prior to the re-excavation of the Kuiseb Valley that involved incision to some 50 m below the base of the Oswater Conglomerate in the canyon reach (Fig. 51). The Homeb Silts were subsequently deposited up to 45 m above the present Kuiseb River bed. Whereas the Homeb Silts are an unconsolidated micaceous valley-fill deposit, the Oswater Conglomerate is an indurated, well-lithified unit. Therefore, the  $^{14}\text{C}$  dates of 28 000 - 33 000 BP for that Oswater exposure, in terms of the deposition of this formation, appear unreliable. Butzer and Vogel (pers. comm. 1983) suggested that the anomalous values obtained for the Oswater Conglomerate probably reflect the last phase of carbonate mobilisation at that outcrop. They postulated that the remobilisation of carbonate in the Oswater Conglomerate matrix may have been influenced by the higher groundwater levels associated with the partial filling of the lower Kuiseb Canyon by the Homeb Silts in the Late Pleistocene.

Deposits similar to the Oswater Conglomerate have been recorded in other large rivers draining across the Namib Desert (Table B.3). Gevers (1936) noted fluvial terraces in the Swakop and Khan Rivers to the north of the study area. As mentioned earlier, Mabbutt (1952) described conglomeratic terrace deposits within the incised Ugab River (Fig. 65). Korn and Martin (1957) also reported the occurrence of calcified terrace deposits, up to 65 m above, and flanking, the present river beds of the Kuiseb, Swakop, Omaruru and Ugab Rivers. Deposits similar to the Oswater Conglomerate have been found in the Huab, Koigab, Unjab, Kharugaiseb and Hunkab Rivers on the Skeleton Coast (Ward, 1982), and, more recently, in the Engo and Kunene Rivers. Ward *et al.* (1983) proposed a further correlation of the Oswater Conglomerate with the Manome Conglomerate which has been described by Soares Carvalho (1961) from the Angolan sector of the Namib Desert.

Thus, the initial aggradational phase within major, westward-flowing rivers in the Namib tract subsequent to the deep incision of their courses during the Late Cenozoic appears to be a ubiquitous event. Calcified gravel terraces flanking these large rivers testify to a greater stream competency during this aggradational phase than is apparent in the modern courses. Although this more effective palaeo-hydrological regime is attributed to a high, but seasonal, rainfall in the catchment areas, arid conditions nevertheless prevailed in the Central Namib.

The Oswater Conglomerate is the earliest record of an association between the incised Kuiseb drainage system and dunes derived from an early sand sea to the south of the river. This relationship is dated provisionally to the Early to Middle Pleistocene. Circumstantial evidence suggests that the northward encroachment of dunes from this ancestral Namib Sand Sea may have contributed to the northwesterly alignment of the Lower Kuiseb River, a trend which had been attained prior to, or simultaneously with, the deposition of the Oswater gravels.

## 2.7 Hudaob Tufa Formation

### 2.7.1 General

The occurrence of tufa deposits in the Kuiseb Valley had not been documented prior to this investigation. These crust-like carbonate deposits (Fig. 66) were mentioned briefly by Yaalon and Ward (1982) in their observations on calcretes in the Central Namib Desert. The best example of a tufa in the study area is located in a left bank tributary of the Kuiseb River c. 70 km upstream from Gobabeb (Fig. B.1). This short tributary and immediate environs, known to the indigenous Topnaar people as *Gai !Hutaob* or *!Hutaob* (Ward and Van Wyk, 1985), constitutes the type locality for the newly-proposed Hudaob Tufa Formation.

The type locality, at 23°42'S and 15°31'E, is approximately 10 km farther upstream from the position of Hudaob normally shown on published topographic maps. The type locality and a schematic type section are displayed in Fig. 67, which also shows the approximate distribution of most of the Hudaob Tufa deposits. At Hudaob, the irregular draping and patchy preservation of the thin tufa carapace (Fig. 66) did not permit the construction of a comprehensive type section.

### 2.7.2 Distribution and thickness

The tufa deposits are confined mainly to the deep canyon sector of the Kuiseb River (Fig. 67) where exposures are situated in steep, gully-like tributary washes (Fig. 66), or in sheltered, mostly south-facing, aspects, such as those in the WA 128A beacon area. Thin tufa crusts were also noted at scattered localities within the dissected gramadulla zone adjacent to the canyon reach of the Kuiseb. Tufa carapaces occur, in places, on the mesa-like outcrops of Tertiary sediments flanking the Kuiseb canyon, e.g., at Carp Cliff (Fig. 67). Thin seams of tufa-like carbonate were noted on, and in, joints within the granites exposed between Gobabeb and the Kharabeb (Aussinanis) - Kuiseb confluence (Fig. B.1). A large mound of tufa-like material, containing abundant salts, is situated close to the confluence of the Natasspruit and the Kuiseb River near the base of the Escarpment (Fig. B.1).

The scattered distribution and relatively isolated occurrences of the Hudaob Tufas hindered the recognition of the lower and upper boundaries of this formation. Thus the stratigraphical position of these deposits is still uncertain. This problem is further aggravated in that the tufas formed at different periods, both those within one deposit and those scattered over their distribution area. However, from their positions within the Kuiseb canyon, the main tufa phase(s) post-dates the deep incision of the Kuiseb drainage system and the development of the associated gramadulla network. Several large tufa carapaces extend from a level higher than that of nearby Oswater Conglomerate exposures to an equivalent height below the base of those rudaceous outcrops (for example, type section, Fig. 67). This altitudinal relationship suggests that those tufa deposits post-date both the Oswater Formation and the subsequent re-incision by the Kuiseb River. The upper limits of the Hudaob Formation are also poorly defined. However, water-worn tufaceous clasts were noted in the Gobabeb Gravel Formation, implying a pre-Terminal Pleistocene age for some Hudaob Tufa accumulations.

The majority of Hudaob Tufa deposits form thin (0,1 - 3 m thick) carapaces resting directly on a Late Precambrian - Cambrian substrate (Figs. 66, 67). At some localities, e.g. Hudaob and DW 248 beacon site, the well-developed carapaces drape irregularly for several tens of metres over a total vertical distance of c. 75 m.

### 2.7.3 Lithology and structure

The tufas are composed predominantly of calcium carbonate, although the effervescent appearance of some deposits implies the presence of salts at those sites. Slabs of locally-derived Damaran schist are commonly incorporated in the basal portions of the larger tufas. The well-developed carapaces have a porous, vesicular texture which is considered typical of tufa deposits (Blatt *et al.*, 1980, p. 479; Sweeting, pers. comm., 1981). Fragments of vegetation, replaced by calcium carbonate, were noted in several exposures and include grassledge stalks and leaves (Fig. 68). The larger tufa deposits also display rounded, vesicular, possibly biogenic structures (Fig. 69) which, in places, are grouped into compound features. At the type locality, the uppermost section of the tufa (Fig. 67) comprises a carbonate-cemented reddish, quartz arenite. The constituent quartz grains closely resemble those in the modern dune sands in the Hudaob vicinity.

Greyish, laminated, dense calcium carbonate, cropping out at a solitary exposure between the Kamberg and the Kuiseb canyon at about 23°35'S and 15°37'E (Fig. 67), was identified as travertine (*sensu* Blatt *et al.*, 1980, p. 479). This small deposit, c. 0,5 m thick, has been included in the Hudaob Tufa Formation. The distinctive exposure rests on Damaran schist at the base of a low erosional scarp cut into the Tsondeb Sandstone. The uppermost 0,1 m of this travertine deposit is formed by low-relief domical structures comprising finely-laminated calcium carbonate (Fig. 70). These small-scale features are best explained as stromatolites and both laterally-linked hemispheroids (LLH) and discrete, vertically-stacked hemispheroids (SH) were recognised in the travertine deposit (terminology after Logan *et al.*, 1964).

### 2.7.4 Mode of origin

The predominantly calcium carbonate composition and porous texture of these crusts, as well as their occurrence in steep tributary washes of the Kuiseb, at relatively sheltered sites and in the vicinity of present-day see pages, point to their origin as calc tufa precipitates. The pedogenic calcretes of the Kamberg Formation are likely to have been the principal calcium carbonate source of many Hudaob Tufa deposits. The calcified sediments of the Tsondeb Sandstone, Karpfenkliff Conglomerate and Oswater Conglomerate Formations provide another potential carbonate source. The influence of both inorganic and plant-induced precipitation of calcium carbonate from groundwaters is apparent in the Hudaob Tufa deposits.

The tufa carapaces in the Kuiseb canyon are accumulations of calcium carbonate precipitated from surface waters at seepage sites during periods when groundwater was abundant. The steep gradient and broken terrain of the tributary washes are likely to have facilitated a decrease in partial pressures of the surface waters seeping down those gullies and hence favoured the precipitation of calcium carbonate. In addition, the high ambient temperatures normally experienced in the Kuiseb canyon might have promoted the evaporation of surface waters in the see pages and thus calc tufa precipitation. The development of the larger tufa carapaces in the Hudaob Formation, such as the one exposed at the type locality (Fig. 71a), can be reconstructed by comparison with a modern tufa-depositing seepage site (Fig. 71b).

The vesicular and porous texture of several Hudaob Tufa deposits (Figs. 69, 71a) can probably be attributed to plant-induced calcium carbonate precipitation, similar to that observed at modern springs and see pages in the Naukluft Mountains, south of the study area (Fig. 72). A moss, probably *Barbula* sp. (Fig. 72, inset), growing in the seeps and on

the small waterfalls at these Naukluft sites is instrumental in precipitating calcium carbonate from the surface waters. Thus organically-controlled calcium carbonate deposition appears to be responsible for the porous texture and rounded vesicular structures observed in the Hudaob Tufa exposures. Similarly, the replacement of plant fragments by calcium carbonate, as is evident on several Hudaob Tufa deposits, was noted on the small waterfalls at the modern Naukluft tufa sites. At those localities, pieces of local vegetation were commonly trapped in scours and potholes on the waterfalls where their subsequent replacement by calcium carbonate (Fig. 73) was probably aided by the break in slope of the river/seepage course and the growth of algal organisms on the plant fragments.

The development of the stromatolitic texture in the travertine deposit is ascribed to the carbonate-precipitating activity of algae in shallow waters at a seepage site. There is no indication of a modern spring or shallow, small pan at the travertine site under the present conditions. A similar lack of present-day seepage is apparent in the vicinity of many, but not all, Hudaob Tufa carapaces within the Kuiseb canyon.

The Hudaob Tufa deposits, therefore, originated during past periods of remobilisation and precipitation of calcium carbonate derived from earlier pedogenic calcretes and calcified rudaceous and arenaceous sediments. It is tempting to speculate that these periods of relatively high groundwater levels and surface see pages were a consequence of greater rainfall in the Central Namib. Such episodes may relate to oscillations of the climatic regime that has prevailed in the Central Namib during the Quaternary. However, the duration of the periods of climatic amelioration were limited because any sustained humid climate(s) during the Quaternary would have resulted in extensive dissolution of the Kamberg Calcrete (Yaalon and Ward, 1982). This contention is further supported by the occurrence of reddish, dune-derived quartz grains in the uppermost part of the large tufa at Hudaob (the type locality). This observation implies that dune sands were present at one locality at least on the southern rim of the Kuiseb Canyon during the deposition of the large tufa carapace at Hudaob.

### 2.7.5 Age and correlation

Most of the Hudaob Tufa deposits post-date the Oswater Conglomerate Formation which has provisionally been assigned an Early to Middle Pleistocene age. The upper limits of the Hudaob Formation are possibly demarcated by the Gobabeb Gravel Formation which, on the basis of rolled Middle Stone Age (MSA) artefacts, is dated to the Terminal Pleistocene (Table 2). These stratigraphical relationships indicate that many of the Hudaob Tufas were deposited between the Middle and Late Pleistocene. The possibility of several phases of tufa formation at one site or of non-synchronous deposition at different sites should, however, be considered in evaluating the age of the Hudaob Tufa deposits.

The isolated and scattered occurrence of Hudaob Tufa deposits in the Kuiseb Valley, as well as their uncertain stratigraphic position, has not facilitated their correlation with similar calc tufas exposed elsewhere in the Namib tract. For example, north of the Kuiseb River, a large composite tufa was noted at the Soutberg, on the northern bank of the Swakop River in the Central Namib (Fig. 74). At sections of this Soutberg occurrence, carbonate and other salts were actively precipitated when the site was visited in October 1981 and the modern vegetation cover included the reed, *Phragmites australis* (Cav.) Trin. ex Steud. A number of tufa deposits were found along the Skeleton Coast (Northern Namib), commonly in the vicinity of modern springs, including Genssenwasser (Koigab River), Mowe Bay area, and Okau waterhole. The

largest and most impressive tufa deposits, e.g. at Blasskranz, Tsams Ost and Tsams West, are to be found in the Naukluft Mountains, which form the Escarpment and eastern edge of the Namib tract south of the study area. Several localities in the Naukluft Mountains are, as noted earlier, active tufa-precipitating sites today (Fig. 71b).

From the above observations it is apparent that the formation of Hudaob Tufa deposits could have overlapped, throughout the Quaternary, with that of other tufa exposures in the Namib tract. These episodes may possibly be correlated with tufa formation during short-lived periods of higher rainfall in an otherwise predominantly arid Namib tract. The palaeo-environmental significance of these tufa - deposits has not, as yet, been fully explored and provides an avenue for further investigation into past climatic changes in the Namib Desert during the Quaternary.

## 2.8 Homeb Silt Formation

### 2.8.1 General

Remnants of flat-lying, silty deposits are preserved up to 45 m above the present Kuiseb River in sheltered localities adjacent to the lower canyon - upper valley sector of the main river course (Fig. 75). These localities are a consequence of the gullied dissection of bedrock to form the gramadulla terrain adjacent to the Kuiseb canyon. In this report, the term "embayment" is used to refer to such settings along the Kuiseb Valley; it has been adapted from McKee (1938) who used it to describe similar environments along the Colorado River.

The unconsolidated, chiefly silty deposits, prominently exposed in the Oswater - Homeb sector of the lower Kuiseb canyon (Fig. B.1), have been accorded considerable attention by previous workers. The various names used in earlier descriptions are summarised below:

Goudie (1972) briefly mentioned the occurrence of horizontally-bedded, fine-grained sediments banked up in tributaries near Oswater which Scholz (1972, p. 40) called "fossil silt terraces." Rust and Wieneke (1974, 1980) referred to these exposures as the "Oswater lake deposits" and Sawyer (1976, provisional legend) named the unconsolidated, micaceous sediments "Unit 37, Oswater II". Marker (1977) referred to "water-laid micaceous silts" (p. 205) which were later called "relict vlei silt" by Marker and Müller (1978, p. 151, 160). These last-mentioned authors proposed the Oswater - Homeb area as the type locality, although no formal name was given to the deposits. Ollier (1977, p. 209) introduced the name "Homeb Silts" and Vogel (1982) used the terms, "Oswater lake deposits" and "Homeb silts", concurrently in his assessment of the age of the silt terraces. Ward *et al.* (1983) followed Ollier (1977) and referred to these sediments as the Homeb Silts.

Ollier's (1977) terminology has been adopted here and the fine-grained deposits in the Lower Kuiseb Valley are called the Homeb Silt Formation. The type locality (23°38' - 39'S; 15°11' - 12'E) is close to the present Topnaar settlement of Homeb and incorporates part of the area proposed earlier by Marker and Müller (1978). The c.25 m thick exposure in the north-bank tributary gully between Department of Water Affairs beacon DW 303 and the Hope - Kuiseb confluence constitutes the type section. The type locality and section of the Homeb Silt Formation is shown on the distribution map, Fig. 76. Additional detailed, composite sections through the Homeb Silts in the Homeb/DW 303 and Oswater areas were provided by Marker and Müller (1978, p. 154).

Although the Homeb Silts form at least two terraces in many

places (Rust and Wieneke, 1974, 1980; Marker, 1977; Marker and Müller, 1978; Vogel, 1982, Fig. 75), these deposits have been treated here as a single sedimentological unit. This interpretation follows that of Sawyer (1976), Ollier (1977) and Marker and Müller (1978).

### 2.8.2 Distribution and thickness

Exposures and sub-outcrops of the Homeb Silts are distributed over c. 62 km of the lower canyon - upper valley reach of the Kuiseb River between Gomkaeb and about Soutrivier (Fig. 76). Near Gomkaeb, the upper surface of the Homeb Silts is preserved at c. 530 m altitude in a tributary canyon below the beacon, WA 267 (Fig. 76). The most downstream silts are situated at an altitude of c. 390 m in the Soutrivier area. The previously known limits of the Homeb Silts, between Gobabeb and the Gorob - Kuiseb confluence (Marker and Müller, 1978), have thus been extended in both an up- and a downstream direction.

Minor silt exposures were noted in shallow embayments along the right bank of the Kuiseb between Klein Klipneus and Klein Klip (Fig. 76). These silts, lithologically similar to the thicker deposits farther upstream, could be relict patches of Homeb Silts but this identification requires clarification.

At some localities, e.g., the DW 304/B beacon, DW 306 beacon, and Natab areas (Fig. 76), the Homeb Silts abut onto Oswater Conglomerate, a relationship also reported by several earlier workers (Marker, 1977; Ollier, 1977; Vogel, 1982). Therefore the Homeb Silts were deposited only after the incision of the Kuiseb River following the accumulation and cementation of the Oswater Conglomerate. The upper limits are formed by unconsolidated fluvial deposits, called here the Gobabeb Gravel Formation, which overlie, and in places truncate, the Homeb Silts. At several localities, notably in the Hope River - Oswater section, locally-derived tributary wash sediments, also truncate and overlie the Homeb Silts (Fig. 76). These gravel deposits form several terrace levels at the mouths of the tributary washes.

The base *per se* of the Homeb Silts was not located and only the bank contacts with Damaran bedrock or Oswater Conglomerate were observed. In the right bank embayments, a thin wedge of angular quartz-schist gravels and micaceous sands, derived locally from the bedrock, commonly underlies the Homeb Silts (Marker and Müller, 1978; type section, Fig. 76). The maximum thickness recorded in anyone vertical exposure of Homeb Silt is about 25 m, although the highest-lying sediments were up to 45 m above the present Kuiseb River bed. The elevations of the basal parts of these exposures ranged from nearly c. 1 m to c. 30 m above the modern Kuiseb course.

### 2.8.3 Lithology and structure

The Homeb succession consists mainly of unconsolidated, micaceous, yellowish-brown to -grey muddy silts with lesser amounts of coarser, brownish to greyish silts and reddish-brown sands (Fig. 76, type section; Fig. 77). Wedges and lenses of locally-derived angular gravels and sands are interbedded in the fine-grained succession (Fig. 77).

The yellowish, finer-grained muddy silts (5 - 7 phi, Marker and Müller, 1978) constitute the bulk of the Homeb Formation, commonly forming layers 0,1 - 1,5 m thick that are massive to finely-laminated and comparatively resistant to erosion (Fig. 77). Abundant platy mica in these silts causes varying degrees of fissility of the hardened layers (Marker and Müller, 1978). Surface weathering has been instrumental in re-distributing silt-sized mica particles as a mud drape down the face

of many Homeb Silt exposures. This secondary process, also reported by Marker and Müller (1978), obscures details of the sedimentary structures preserved within the Homeb beds. Thin hardpan horizons, less than 0,05 m thick, are associated with some of the yellowish silt beds.

The more resistant yellowish silts alternate irregularly with less resistant layers (Figs. 77, 78) composed of coarser, biotite-rich silts (4 - 5 phi, Marker and Müller, 1978), reddish-brown sands and locally-derived angular gravels and micaceous sands. The up to c. 1 m thick, biotite-rich units are predominantly brownish to greyish but greyish-green layers were also observed. The sandy deposits form up to 1,5 m thick lenses and the reddish-brown colour is due to a mixture of dune- as well as river-derived quartz grains, accompanied by conspicuous flakes of mica (mostly biotite).

Wedges and lenses, up to 0,5 m thick, of angular quartz-schist gravel and coarse biotite-rich sand interdigitate with the fine-grained Homeb deposits in the north bank embayments. This coarse-grained material represents local hill wash debris. The frequency of these units within the Homeb silts is highest in those parts of the embayments which are far removed from the Kuiseb River, suggesting relatively low sedimentary input from the gramadullas during the accumulation of the Homeb Silts.

Generally, the Homeb Silts are horizontally disposed (Figs. 75, 78), but in some embayments the beds are inclined gently towards the Kuiseb River or, at isolated localities, even dip at low angles away from the main course (Fig. 79). The silt-sand layers are distributed irregularly throughout the Homeb succession (Fig. 78), but locally regular alternation between silty-sand beds, 0,5 - 1 m thick, and resistant silt beds, up to 0,5 m thick, was observed (Fig. 80). Cemented nodules and pedotubules were recorded in the upper parts of these silty-sand layers and are commonly present in the hardened silt beds. Thin (0,025 m thick) horizons of gypsum crystal aggregates are associated with some of the silt beds' in the regularly layered exposures.

In contrast to the massive to finely-laminated nature of the yellowish muddy silt layers, coarser silt interbeds exhibit two principal types of small-scale stratification, viz., horizontal (including parallel) lamination (Fig. 81a) and climbing-ripple (or ripple-drift) cross-lamination (Fig. 81b) (terminology after McKee, 1966; Jopling and Walker, 1968). These structures are best developed in the relatively coarse, dark-coloured silt lenses and in layers of yellowish-green to greyish-green, biotite rich silts. Although climbing-ripple cross-lamination was documented by Marker and Müller (1978), the significance of these micro-structures has apparently been overlooked by previous workers.

Desiccation cracks, also recorded by Marker and Müller (1978), are particularly abundant in the yellowish muddy silt layers of about the upper third of the Homeb sequence (Fig. 77). These features are open V-shaped wedges in transverse section or sand-filled cracks forming a polygonal cast pattern when viewed from below (Fig. 82).

Small channel-like structures, mostly less than 0,3 m deep, are cut into the silty strata at various levels in the Homeb succession. The base of these erosion channels (Marker and Müller, 1978) usually consists of small pebble and coarse sand-sized intraformational mud clasts.

Penecontemporaneous deformation structures (sensu Reineck and Singh, 1975, p. 75-81; Selley, 1976, p. 224-226; Blatt *et al.*, 1980, p. 188-193) occur in some of the Homeb beds. Irregularly contorted stratification and convolute lamination are the most common structures (Fig. 83; terminology

after McKee *et al.*, 1962; Selley, 1976, p. 224-226). Convolute bedding, flame and small-scale slump structures, in places minutely faulted, have also been documented from some beds (Marker and Müller, 1978).

Additional disturbance of the internal stratification in the Homeb Silts was due to biogenic activity. Traces of plant roots can be recognised by the oxidised stains and patches penetrating the internal stratification of some silt layers (Figs. 81a, 84). Local concentrations of pedotubules (Fig. 84) resemble the dense root network of some grasses (notably *Cladoraphis spinosa*), growing at present in the Kuiseb bed. Further evidence of bioturbation within the Homeb Formation includes horizontal surface trails and burrow-like structures which cut across the bedding and are, in places, preserved as positive micro-relief features (Fig. 85).

Marker and Müller (1978) reported four gastropod species, *Bulinus tropicus* (= *Isodora* sp.), *Biomphalaria pfeifferi*, *Xerocerastus* sp. and *Sculptaria sculptaria* from the Homeb Silts. The specimens shown in their Fig. 3 (Marker and Müller, 1978, p. 160) have been incorrectly labelled and no discrepancy, as intimated in their paper, therefore exists between the identification made by biologists of the South African Museum and Dr. Oberholzer (Appleton, pers. comm., 1983). The joint occurrence of these four gastropod species in the Homeb Silts is interesting in that *Bulinus tropicus* and *Biomphalaria pfeifferi* are extant aquatic snails, whereas the other two, *Xerocerastus* sp. and *S. sculptaria* are terrestrial species characteristic of the arid to semi-arid areas such as SWA/Namibia, Botswana and the northern Cape Province (Appleton, pers. comm., 1983).

A small rodent skeleton, identified tentatively as that of *Paratymus* sp., was found embedded in a silty layer of the Homeb succession in a right bank exposure between Oswater and the DW 307 beacon (M.C. Ward, pers. comm., 1981, Fig. 76). Other bone fragments were also found at that vicinity but these have not, as yet, been adequately identified.

#### 2.8.4 Mode of origin

Previous workers have offered several explanations for the origin of the Homeb Silts:-

- (i) sediments deposited behind a dune dam(s); Goudie (1972), Scholz (1972), Rust and Wieneke (1974, 1980);
- (ii) river endpoint accumulations; Marker (1977), Marker and Müller (1978), Vogel (1982);
- (iii) flood deposits of an aggrading river; Ollier (1977).

This study provides additional evidence, which is outlined below, supporting Ollier's (1977) interpretation.

The general horizontal disposition of the Homeb Silts has been ascribed to their accumulation behind a dune dam (Scholz, 1972; Rust and Wieneke, 1974, 1980) or a series of dune dams that formed as the Kuiseb River endpoint migrated upstream (Marker and Müller, 1978). In this study, no remnants related to dune dam sediments were found within the Homeb succession. However, sandy lenses and wedges consisting of mixed dune- and Kuiseb River - derived quartz grains, as well as abundant mica flakes, are commonly interbedded with the finer sediments typical of the Homeb Formation. These arenaceous beds are similar in composition to the bedload in the present Lower Kuiseb River (Ward, 1984a), suggesting that dune sand was a component of the sediment supply during the accumulation of the Homeb Silts.

It is speculated, therefore, that reddish aeolian dunes encroached into the canyon reach of the Lower Kuiseb River during Homeb times, as they do today. These dunes would have been susceptible to fluvial erosion thereby introducing

aeolian sand grains into the Homeb succession. The absence of such dune fronts is attributed to the poor development of gramadullas, and hence sheltered embayments, along the left bank of the Kuiseb canyon. Moreover, unconsolidated deposits banked up along the left, less sheltered margin of the river course were likely to have been removed during the ensuing re-incision phase by the Kuiseb River.

Between Gomkaeb and Soutrivier, the present Kuiseb River drops c. 115 m in elevation. Over the same c. 61 km, the uppermost surface of the Homeb Silt drops c. 140 m, a longitudinal profile that is sub-parallel to the modern course (Fig. 76). Although a series of dune dams on the lower canyon sector of the Kuiseb River may account for the downsloping gradient exhibited by the Homeb Silt Formation, this trend is, in the writer's opinion, more compatible with that of a river profile.

Fluvial deposition also accounts for those beds which locally dip at low angles either towards or away from the main Kuiseb course. McKee (1938) observed that fine-grained sediments deposited in tributary canyons of the Colorado River by the main stream are generally horizontally-bedded but, in some places, the strata dipped gently towards, or away from, the main stream. He noted that such deposits accumulated rapidly in the protected environs of the mouths of these tributaries during flood stages of the Colorado River. The tributary canyons of the perennial Colorado River are situated in an arid tract where the main river rises in well-watered highlands and, prior to the construction of the large dams, was known for its floods and large-scale fluctuations in river level (McKee, 1938).

Similarly, the Kuiseb River rises in the better-watered, but nevertheless semi-arid, Khomas Hochland beyond the eastern limits of the extreme-arid Central Namib Desert. The Kuiseb catchment, since the Late Cenozoic, has fallen within the Escarpment and interior plateau zones which have experienced a consistently higher rainfall than the Namib (Korn and Martin, 1957). The fine-grained micaceous sediments dominating the Homeb Silt Formation were derived principally from mica schists underlying most of the catchment area. This rock type, on weathering, yields abundant silt-sized mica as well as the fine to medium sand-sized quartz grains characteristic of the present Kuiseb River bedload. The Homeb Silts thus represent the fine-grained fraction of the Kuiseb River load deposited in relatively low-energy environments away from the main stream.

The regularly alternating silty-sand and silt layers (Fig. 80) are reminiscent of muddy sand and mud units described by McKee (1966) from modern fluvial deposits of the Indus River. In the Indus Valley, such units form part of the flood plain deposit in which each (sand + mud) and mud couplet represents a flood episode. Therefore, the similar units in the Homeb succession are attributed to successive flood events in the Lower Kuiseb River at that time. Fluctuating discharge in the Kuiseb River during Homeb times is suggested by the presence of arenaceous lenses and wedges interbedded in the predominantly silty deposits.

The abundance of horizontal- and climbing-ripple (ripple drift) cross-lamination preserved in the Homeb strata provide further support for a fluvial origin of this formation. Although horizontal (or nearly so) micro-stratification is known from a wide variety of environments, climbing-ripple (ripple-drift) cross-lamination is developed where sediment fall-out rates from suspension are high (McKee, 1966). Such conditions are encountered in relatively few environments, e.g., in deposits associated with turbidites, fluvial flood plains, point bars/natural levees and kame deltas (McKee, 1938, 1966; McKee *et al.*, 1967; Jopling and Walker, 1968; Blatt *et al.*, 1980, p. 152).

However, the combination of both horizontal lamination and climbing-ripple (ripple-drift) cross-lamination, as is evident in silty units of the Homeb Formation, has been recognised in many fluvial flood plain deposits (McKee, 1966).

Vertical penecontemporaneous deformation structures, such as the convolute lamination developed locally in some Homeb Silt beds, are also commonly associated with the fine sand/coarse silt deposits of fluvial flood plains (McKee, 1938, 1966; McKee *et al.*, 1967; Selley, 1976, p. 224). The development of convolute lamination is generally ascribed to plastic deformation and at least partial liquefaction of fine sand/coarse silt beds. This structure is indicative of rapid sedimentation of these fine-grained sediments from suspension (Blatt *et al.*, 1980, p. 192-193).

Significantly, a comparison of sedimentary features developed in the modern Kuiseb River with those commonly preserved in the Homeb Silts also points towards a fluvial, flood plain origin for these deposits.

In the contemporary Kuiseb River, abundant biotite-rich silts or sandy silts are deposited adjacent to the main course, commonly in small protected embayments on the flood plain, during flood events. Grain size and composition analyses of these modern sediments are in good agreement with those of the Homeb Silt deposits (Marker and Müller, 1978). Horizontal micro-stratification and climbing-ripple (ripple-drift) cross-lamination, common in the Homeb succession, are well displayed in the modern flood silts (Fig. 86). Similarly, convolute lamination was observed in freshly-deposited, silty-sand layers overlain by muddy silts on the margin of the modern Kuiseb River (Fig. 87).

An isolated, oxidised organic layer interbedded with silty deposits in a Homeb exposure near DW 307 beacon closely resembles an organic flotsam deposit resting on micro-stratified silts on the modern Kuiseb flood plain (Fig. 88). In the contemporary environment, the flotsam consists of debris brought down by the Kuiseb floods (Fig. 88b, inset), providing additional evidence of lateral flooding in the Kuiseb River during the accumulation of the Homeb Silt Formation.

Desiccation cracks usually develop in the muddy silts deposited by the modern Kuiseb River after the irregular floods have subsided or terminated. With continued subaerial exposure, these features may be filled with windblown, river-deposited sands (Fig. 89), producing a pattern similar to that noted in some Homeb Silt beds (Fig. 82). The dense concentration of root-like pedotubules implies periods when the Homeb Silt deposits were exposed for sufficient time to allow the growth of vegetation, such as *Cladoraphis spinosa*, on the former Kuiseb flood plain. This type of vegetation can today establish itself in the river bed and flood plain over a period of several years, particularly when modern Kuiseb floods are of low energy or do not occur at all (Ward, 1984a). Therefore these pedotubules also indicate subaerial exposure of the Homeb sediments during their accumulation.

Similarly, the presence of hardened pedotubules and nodules in some silty-sand layers and silt beds implies fluctuating ground-water levels and interrupted sedimentation facilitating incipient calcretisation. The thin hardpan horizons in the upper part of the Homeb succession probably reflect hydromorphic conditions and some diagenesis (Butzer, pers. comm., 1983). The greyish and greenish colour of some silt layers is attributed to the reduction, and hence incipient gleying and mottling, associated with excess water for at least intermittent periods during the accumulation of the Homeb Silts (MacVic-ar *et al.*, 1977, reprinted 1981).

These comparative observations outlined above suggest that the Lower Kuiseb River, at least, experienced an ephem-

eral/intermittent fluvial regime during the deposition of the Homeb Silts. Arid conditions within the Central Namib are indicated by the occurrence of reddened, aeolian dune sand grains and the formation and preservation of thin hardpan horizons and gypsum crystal aggregates in the Homeb succession. Nevertheless, the occurrence of Homeb Silts up to 1,5 km away from the modern Kuiseb course (Figs 76, 90) points to a more competent flow regime than that envisaged for the accumulation of the Homeb Silts at an endpoint of the former Kuiseb River (*sensu* Marker and Müller, 1978; Vogel, 1982).

The combination of an intermittently flooding Kuiseb River and arid conditions in the Namib would account for the occurrences of both aquatic and arid terrestrial gastropod species in the Homeb Silts. *Bulinus trapicus* and *Biomphalaria pfeifferi* were probably derived from pools restricted to the Escarpment and Khomas Hochland sectors of the Kuiseb River, whereas *Xerocerastus* sp. and *S. sculptaria* indicate arid (? to semi-arid) conditions away from the watercourse.

The absence of thick silty deposits characteristic of the Homeb Formation downstream from Soutrivier (Fig. B.1) is attributed to the shape of the Kuiseb Valley in that lower sector. Below Soutrivier, the valley is wide, open and no longer flanked by gramadullas. The chance, therefore, that Homeb-like deposits would be preserved is low. However, biotite-rich silts and clays, as well as gypsum layers, are interbedded with quartzose sands in unconsolidated deposits that underlie Gobabeb Gravels along the southern and northern margins of the present Kuiseb Delta (Fig. B.1). These sediments, informally referred to as the Awa-gamteb muds in this study (section 2.9), might be coastal equivalents of the Homeb Silts.

In summary, therefore, the Homeb Silts are an accumulation of the fine-grained fraction of the Kuiseb River load deposited during flood events in the low-energy environments afforded by the gramadullas adjacent to the main course. Their accumulation, up to 45 m above the present course, is a consequence of aggradation of the Lower Kuiseb River bed. At that time, the main course probably consisted of a sandy bed and thus the Homeb Silts *per se* did not necessarily fill the valley, as has been suggested by proponents (cited earlier) of the dune dam or the river end-point arguments. Although the deposition of the Homeb Silts represents considerable flooding in the Lower Kuiseb River, flow was probably ephemeral, and, at best, seasonal. Climatic conditions in the Escarpment and Khomas Hochland areas largely determined the flow regime in the Kuiseb River during Homeb times, whereas arid conditions appear to have prevailed in the Central Namib. Therefore; aggradation of the Homeb Silts was probably controlled either by a base level change in the lower reaches of the Kuiseb Valley (eustatic control?), or, more likely, a change in the hydrological regime in the catchment area (climatic control?).

#### 2.8.5 Age and correlation

The Homeb Silts post-date the Oswater Conglomerates and pre-date the Gobabeb Gravel Formation. On stratigraphic grounds, therefore, a Middle to Late Pleistocene age is assumed for the deposition of the Homeb Formation.

From stable isotope analyses and radiocarbon dating of some thin calcareous hardpan crusts, gastropod shells and a decayed fragment of wood, Vogel (1982) estimated that the Homeb Silts accumulated between about 19 000 and 23 000 BP (upper Late Pleistocene). Although  $^{14}\text{C}$  dating of carbonates must be interpreted with caution (Callen, Wasson and Gillespie, 1983), the similarity in age between the wood sample (22 000

BP; Pta-2688) and gastropod shells (22 500 BP; Pta-1822) provides a measure of reliability to the ages determined from the calcareous material (Vogel, 1982; pers. comm., 1983).

This proposed age for the Homeb Silts corresponds approximately to that of the Last Glacial Maximum in the Southern Hemisphere (Salinger, 1981). At that time, climatic conditions were more arid in southern Africa (Van Zinderen Bakker, 1976; Tankard and Rogers, 1978), as well as in most other parts of the world (Sarnthein, 1978), than today. Even though arid conditions are likely to have prevailed in the Central Namib, the Kuiseb catchment should also have been affected by drier conditions during the Last Glacial Maximum. Therefore, if the dates for the Homeb Silts are reliable, an anomalous situation exists because the Homeb Silts reflect extensive flooding in the Lower Kuiseb River suggesting greater run-off and hence higher rainfall in the catchment.

Unconsolidated deposits of similar nature and stratigraphic setting have been noted in other large rivers which rise in the interior plateau and drain westwards across the Namib Desert to the Atlantic Ocean, including the Swakop, Omaruru, Huab and Hoanib Rivers (Fig. 1, Table B.3). The most impressive silty deposits are those banked up in gramadullas adjacent to the Lower Hoarusib River in the Northern Namib (Fig. 91). There, flat-lying, silty and sandy deposits, which rise up to 75 m above the present course, are best preserved in north bank tributary canyons. Small scale sedimentary structures include horizontal- and cross-micro-stratification, intraformational mud clasts in small scours, desiccation cracks, as well as numerous shells of *Bulinus trapicus* (identified by Appleton, pers. comm., 1983). A preliminary  $^{14}\text{C}$  analysis of these snail shells yielded an apparent age of c. 33000 BP (Vogel, pers. comm., 1983), suggesting that the Hoarusib deposits accumulated prior to the Last Glacial Maximum.

The widespread occurrence of similar fine-grained deposits in the Namib sector of many westward-draining rivers in SWA/Namibia suggests a regional control of their hydrological regimes during the Late Pleistocene. Climatic change which affected the catchments of these rivers is likely to have governed this regional aggradational event, although the influence of eustatically-controlled sea level changes on river base level cannot be discarded entirely. The apparent anomaly of aggrading, flooding rivers within the Namib at about the Last Glacial Maximum requires further attention because other lines of evidence suggest an increase in aridity in the Southern Hemisphere at that time (Bowler, 1976; Van Zinderen Bakker, 1976; Sarnthein, 1978; Tankard and Rogers, 1978; Hays, 1978; Salinger, 1981; Deacon, 1983).

## 2.9 Awa-gamteb Muds

### 2.9.1 General

Unconsolidated fine-grained deposits, comprising silts, clays and intercalated sand layers, are poorly exposed in 10 to 20 m high scarps that form the approximate northern and southern limits of the present Kuiseb Delta (Fig. 92). Barnard (1975) recognised the low scarps bounding the Kuiseb Delta but gave no further details of their composition and structure. The informal name, Awa-gamteb muds, is proposed here for these fine-grained sediments which may be distal, coastal equivalents of the Homeb Silt Formation, a relationship that requires clarification.

Although arenaceous layers are present, the abundance of silts and clays in these deposits prompted the use of the qualifying term "muds" (Blatt *et al.*, 1980, p. 381; Blatt, 1982, p. 546). The clays are conspicuous because of their absence in the other Cenozoic deposits of the Kuiseb Valley west of the

Escarpment. The geographical name has been adapted from the Topnaar locality, *LAwa-Ilgamteb*, that describes the area along the southern channel (present flood conduit) of the Kuiseb Delta from about B-Area Reservoir downstream to the borehole, Bg 2/77 (Budack, 1977; Ward and Van Wyk, 1985; Fig. 93). The scarp exposure (23°08'S; 14°31'E) c. 2 km south of the borehole, Bg 1/77, provides a reference locality and section for the Awagamteb muds (Figs. 92, 93).

### 2.9.2 Distribution and thickness

The Awa-gamteb muds, restricted to the north-western sector of the study area (Fig. B.1), form most of the low scarps flanking the Kuiseb Delta and front onto the coastal flats (Fig. 93). The Awa-gamteb muds are exposed from c. 10 m above sea level (base concealed), at c. 6 km from the Atlantic Coast, to an elevation of c. 60 m at c. 15 km from the present coastline. Along the north-eastern side of the Kuiseb Delta, the Awa-gamteb muds constitute up to 14 m of the unconsolidated sediment scarp. This northern scarp abuts the Damaran bedrock ridge, known locally as Quarries, although the easternmost limits of the Awa-gamteb muds were located at c. 60 m altitude on the bedrock scarp near Mile - 10 Reservoir (Fig. 93). The Awa-gamteb muds are less well exposed in the scarps south of the Kuiseb Delta since these are partly covered by modern crescentic dunes of the main Namib Sand Sea (Fig. 92). The southern limits of the exposed Awa-gamteb muds are in the vicinity of the Water Affairs wellpoint, LKWP 14. South of the Kuiseb Delta, the eastern limits of the Awagamteb muds are demarcated by a small exposure in an interdune hollow south of the Kuiseb Project beacon, KP 96 (Fig. 93).

The lower boundary of the Awa-gamteb muds was not identified because of the poor exposure. Unconsolidated gravels and sands of the Gobabeb Gravel Formation overlie the Awa-gamteb muds (Figs. 92, 93). This upper contact is rarely well-defined because of the scree-like cover derived from the weathering of unconsolidated Awa-gamteb muds and the Gobabeb Gravels. However, where the contact was cleaned with a shovel, this boundary appears to be uncomfortable. The scarp exposures thus reveal minimum thicknesses only for the Awa-gamteb muds; the thickest sections, c. 15 m, were noted south of the Kuiseb Delta.

### 2.9.3 Lithology and structure

The Awa-gamteb muds consist of flat-lying beds of clayey and silty sediments alternating irregularly with layers of loose, yellowish sands (reference section, Fig. 93). The fine-grained sediments are predominantly dark-coloured to black and consist of layers of muds, micaceous silts and dark biotite-rich sands (Fig. 94). The clayey beds, 0,05 - 0,3 m thick, commonly contain abundant halite that, in places, has distorted the clay layers and formed a crusted upper surface to those beds (Fig. 94). The micaceous silt and silty-sand layers are mostly less than 0,5 m thick whereas the dark biotite-rich sand layers are usually less than 0,2 m thick.

Halite is visible in many of the Awa-gamteb beds, particularly the black mud layers, and local concentrations are also evident in the silty sand layers. Gypsum is commonly associated with the mud and silt beds, particularly in the northern scarp between the Quarries bedrock ridge and Mile - 7 Reservoir (Fig. 93) where thin but conspicuous horizons of small greyish "desert roses" occur (Fig. 95).

Unconsolidated, yellowish quartz sands, in beds up to c. 3 m thick, are interbedded with the fine-grained deposits in the Awa-gamteb succession (Fig. 93). These sands are

chiefly fine- to medium-grained and free of salts and fine micaceous material. No internal sedimentary structures were observed.

### 2.9.4 Mode of origin

The Awa-gamteb muds occur within the coastal tract of the Kuiseb Valley. The abundance of mica in the mud and silt beds, particularly the dark biotite-rich type, points to the Kuiseb River as the principal source. Large quantities of mica-rich sands, silts and clays, derived principally from schistose metasediments of the Damara Sequence exposed in the catchment, are deposited in the Delta and on the coastal flats west of the main Namib Sand Sea by the modern Kuiseb River during heavy floods (Stengel, 1964; Nagtegaal, 1973).

Dark-coloured, silty clays, similar to the Awa-gamteb mud layers, have been described as Kuiseb flood deposits from the modern succession developed on the supratidal flats to the south of the Walvis Bay lagoon (Nagtegaal, 1973). Halite and gypsum, precipitated from shallow groundwater brines under the present extreme-arid climate, are common authigenic components of this succession (Nagtegaal, 1973). The presence of gypsum (roses) and abundant halite in the Awagamteb muds is likewise attributed to the fluctuation of shallow groundwater levels in a former coastal plain or delta environment. The development of these minerals was probably promoted by an arid climate and intermittent inundation of the early coastal flats by sea water, as is still the case today during very high spring tides and storms.

On the basis of grain shape and composition, the loose, yellowish quartz sand layers intercalated in the Awa-gamteb succession can be closely matched to sands forming the coastal, crescentic dunes of the main Namib Sand Sea. This, together with the lack of silty fines in these layers, suggest that the yellowish sandy units are parts of relatively small coastal dunes incorporated in the Awa-gamteb succession. Significantly, Nagtegaal (1973) noted that the bases of barchans are commonly preserved between layers of silts and clays derived from Kuiseb River floods in the modern coastal flat environment. He suggested that groundwaters, rising by capillary action, provide moisture and salts to consolidate the base of coastal crescentic dunes, thus facilitating their incorporation into the contemporary Kuiseb Delta - coastal plain deposits.

During severe, although occasional, floods into the Kuiseb Delta, crescentic dunes can be planed by floodwaters and then capped by micaceous, fluvially-derived silts (Stengel, 1964). The Kuiseb floodwaters promote partial consolidation of the dune sand (Fig. 96a), further favouring the preservation of these deposits. Thus the lower portions of these dunes are sealed into the contemporary sedimentary succession. A measure of the stability and effectiveness of fluvial silt cappings on dune sands can be appreciated from an exposure containing elephant (*Loxodonta africana*) tracks near Rooibank (Fig. 96b). From the tracks, it is apparent that the elephants walked in the muddy deposits, which overlie dune sands, soon after the flood. Subaerial exposure of these muddy silt deposits is confirmed by the well-developed desiccation cracks (Fig. 96b). Elephant tracks, amongst others preserved in the flood deposits of the Kuiseb Delta, had already been noted in the last century (Wilmer, 1893). These tracks could also predate Alexander's journey down the Kuiseb River in 1837 because he noted that elephants were to be found farther north in the Swakop River (Alexander, 1838, reprinted 1967). Therefore, the muddy silt deposit containing the elephant tracks (Fig. 96b) has formed a protective capping on those dune sands for at least, but probably longer than, a hundred and fifty years.

These observations also indicate that the Awa-gamteb muds accumulated in a coastal plain - delta environment. The eastern limit of the coastal flats during Awa-gamteb times was probably formed by the bedrock scarp between Haob/Mile - 16 area and the Quarries ridge. The Awagamteb muds are likely to have formed a continuous deposit between the southern limits near LKWP 14 and the main Walvis Bay - Rooikop road (Fig. 93) that was subsequently dissected by the modern Kuiseb River forming the present Delta. Arid conditions prevailed in the coastal tract and pale-coloured dunes were associated with the extreme distal sector of the Kuiseb River during Awa-gamteb times.

#### 2.9.5 Age and correlation

The restricted coastal distribution of the Awa-gamteb muds, as well as their poor exposure, precluded their comparison with the other Cenozoic successions in the Kuiseb Valley. The Awa-gamteb muds are overlain by the Gobabeb Gravels which also truncate the Homeb Silt Formation. The Awa-gamteb muds are interpreted as extreme distal flood deposits of an earlier Kuiseb River whereas, the Homeb Silts, which likewise are flood deposits, are restricted to the lower canyon - upper valley reach of the Kuiseb. Both these units are predominantly unconsolidated micaceous deposits and it is suggested here that the Awa-gamteb muds are the coastal, distal equivalents of the Homeb Silt Formation. This correlation, and the presence of rolled Middle Stone Age (MSA) artefacts in the overlying Gobabeb Gravels, implies a minimum, Late Pleistocene age for the Awa-gamteb muds.

Unconsolidated, fine-grained deposits, similar to the Awa-gamteb muds, have been noted at the mouths of several large rivers traversing the Namib desert. Farther north, in the Omaruru Delta, silt and sand deposits are capped by an unconsolidated gravel terrace containing rolled MSA artefacts at c. 21 m above sea level (Korn and Martin, 1957). A thick unconsolidated - sediment wedge, forming sea-facing cliffs up to c. 40 m high, was noted in the Unjab Delta on the Skeleton Coast (Fig. 97). Cross-stratified coastal dune sands, mud lenses and sands are overlain by gravels (Fig. 97). A similar, but lower lying sediment terrace was noted on the south side of the Hoarusib River mouth.

This widespread occurrence of Awa-gamteb type sediments suggests that, during the Late Pleistocene, conditions favouring their deposition extended over much of the central and northern Namib.

### 2.10 Gobabeb Gravel Formation

#### 2.10.1 General

Most river courses in SWA/Namibia are accompanied by terraces, rising 10-20 m above the present bed, that are covered by non-calcified gravels (Korn and Martin, 1957). Both rolled and unrolled Middle Stone Age (MSA) artefacts have been found at numerous localities in these gravel deposits (Korn and Martin, 1957). Similar gravel-capped terraces have been recognised in the Kuiseb Valley where these features are particularly evident in the lower canyon to delta sector (Fig. 98).

Scholz (1968) and Goudie (1972) noted a 10 - 20 m terrace level between Natab and Gobabeb. Rust and Wieneke (1974, 1980) identified an upper and a lower Homeb terrace level. The latter is formed by tributary washes and is composed mainly of locally-derived gravels from the gramadullas. Marker (1977) also recorded two terrace levels in the Homeb area, the lower of which is a product of local hillwash debris. Ollier (1977) reported terrace levels several metres above the

present Kuiseb River, the development of which post-dated the Homeb Silts. Marker and Müller (1978) suggested that the Kuiseb River cut down to its present level in two stages after the emplacement of the Homeb Silts, forming a lower terrace level concealed partly by younger sands and gravels. Vogel (1982) also noted fluvial deposits "partly banked up" against the Homeb Silts as a "12 m terrace" (p. 203). He suggested that the "12 m terrace" at Homeb was cut during the re-excavation of the Kuiseb Valley fill formed by the Homeb Silts.

These above-mentioned terrace levels not only incorporate bedrock material derived locally from the tributary washes, but also gravels composed predominantly of rounded to well-rounded vein quartz, metaquartzite and quartzite clasts (Fig. 99). This clast assemblage, as noted earlier, is typical for the Kuiseb drainage system (Fig. 29). The deposits incorporating these clast types, as well as water-worn clasts derived from the Oswater Conglomerate (Fig. 99), form low terraces flanking the Kuiseb River (Fig. 98) and are recognised here as the Gobabeb Gravel Formation. The geographical name is taken from the locality of the Namib Research Institute (formerly Namib Desert Research Station) at Gobabeb, which is a corruption of the original Topnaar place-name, /Nomabeb. The thin gravel-capped terrace on the east side of the Gobabeb Wash near the Namib Research Institute (Fig. 98) is the type locality (23°34'S; 15°03'E) of the Gobabeb Gravel Formation, which, together with the type section, is shown in Fig. 100.

#### 2.10.2 Distribution and thickness

Gobabeb Gravels occur on low-lying terraces that flank the Kuiseb River from about the Uspass Bridge, near the base of the Escarpment, downstream to the Delta area (Figs. B.1, 100). Similar geomorphological features were also noted in the Gaub River upstream from the Dagbreek farmhouse, and in its tributary, the Witberg River (Fig. B.1). In this study, emphasis was placed on those terrace "deposits in the Kuiseb River.

In the upper reaches, between the Uspass Bridge and about Gomkaeb (Fig. 100), the Gobabeb Gravels are semi-consolidated whereas, farther downstream, these deposits consist mainly of a thin, uncemented gravel layer, rarely more than several clasts thick. Bench-like bedrock terraces, in places capped by conglomerate up to 3 m thick, were noted some 3 - 5 m above the present Kuiseb flood plain between the Koam-Kuiseb confluence and the Kuiseb Canyon Bridge (Fig. 100). Scattered deposits of lightly-cemented conglomerate form low-lying terraces along the Kuiseb River in the deeply-incised reach between the Nausgomab-Kuiseb confluence and about Gomkaeb (Fig. 100).

Several levels of Gobabeb Gravels were noted in the lower canyon, ranging from c. 5 m to about 30 m above the present Kuiseb bed (Fig. 101). Where the Kuiseb canyon widens into an open valley downstream from Natab, a thin layer of Gobabeb Gravels is spread over the bedrock or the Homeb Silts. These deposits occur from several metres to c. 25 m above the present Kuiseb River bed and can be traced for up to 1 km from the modern course in this lower reach (Figs. B.1, 98, 100). Small patches of sandy-pebble conglomerate and arenite are cemented onto granites exposed in the Narob - Auses area, some 12 - 16 km downstream from Gobabeb (Fig. 100).

No Gobabeb Gravels were recorded along the Kuiseb River between about Bubuses, near Swartbank, and Ururas (Fig. 100), where they are either hidden under the present river alluvium or because the Kuiseb occupied a more southerly course at that time. West and north-west of Ururas, the Gobabeb Gravels are patchily exposed in several interdune valleys



(Figs. B.1, 100). Farther westwards, they overlie Awa-gamteb muds to the south and north of the present Kuiseb Delta.

The lower, stratigraphic boundary of the Gobabeb Gravels is formed by the Homeb Silts in the lower canyon - upper valley reach and by the Awa-gamteb muds in the delta area. The upper boundary of the Gobabeb Gravels is marked by a geomorphological event, viz., the development of the modern Kuiseb course. The Gobabeb Gravels are up to some 5 m thick in the upper reaches of the Kuiseb Valley and mostly less than 2 m thick in the lower reaches, where the exposures are usually a thin gravel layer only. In the delta area, the Gobabeb Gravels are again up to 5 m thick.

#### 2.10.3 Lithology and structure

Resistant clast types typical of the Kuiseb drainage system, viz., metaquartzite, vein quartz and Etjo quartzites, constitute the bulk of the gravels in the Gobabeb Formation. These rounded to well-rounded clasts have been derived largely from the Oswater and Karpfenkliff Conglomerate Formations. The high degree of rounding of these clasts (Fig. 99) was thus attained during these previous cycles of abrasion. The gravel deposits downstream from Natab contain an abundance of iron oxide-coated quartz clasts which impart a distinctive, yellowish-brown colour to those exposures.

Minor, but characteristic, clast types in the Gobabeb Gravels include:

- (i) water-worn clasts of Oswater Conglomerate (Fig. 99);
- (ii) thin hardpan fragments derived from the Homeb Silts;
- (iii) rod-like pieces of calcified vegetation, mostly less than 0,2 m long, that closely resemble roots and stems of *Acanthosicyos horrida* (Fig. 102), *Salvadora persica* L. and *Phragmites* sp.;
- (iv) rolled MSA artefacts, including blades made from metaquartzite, vein quartz, Etjo quartzite and dolerite;

In the upper canyon and more proximal reaches, slabs of mica schist are commonly found in the low-lying conglomerate terrace deposits. In the distal reaches, downstream from Ururas, the typical Kuiseb-derived clast assemblage is supplemented by:

- (i) greyish, sub-rounded to angular, Damaran marble and metaquartzite clasts, derived from the Swartbank-*IHaigowab* areas (Fig. 100);
- (ii) black, sub-rounded dolerite clasts (some appear to be rolled artefacts) that are conspicuous in the pale-coloured, quartz-rich gravel exposures;
- (iii) rounded to sub-angular fragments of the uranium-bearing, calcified gravels and grits that today are exposed along the northern (right) bank of the Kuiseb between Soutrivier and about Swartbank (Fig. 100);
- (iv) sub-angular fragments of reddish-brown, gypsiferous sediment derived from the plains along the northern (right) bank between Swartbank Mountain and about Rooibank (Fig. 100).

Maximum clast size decreases from boulder-large cobble size near the base of the Escarpment to cobble-pebble size in the lower canyon - valley reach. In the delta exposures, pebbles and cobbles of both the resistant and locally-derived clasts (outlined above) occur and commonly form a thin surface lag overlying pebbly sands comprising dune- and river-derived quartz grains as well as mica flakes.

The boulders and large cobbles in the proximal exposures are, in places, crudely imbricated, their long (a-) axes aligned approximately transverse to river flow. These clasts are commonly supported in a matrix of quartz sand and pebbles. In

the canyon sector, several exposures of cemented Gobabeb Gravels are both horizontally- and cross-stratified (Fig. 103). The pebble-studded arenite near Auses, c. 15 km downstream from Gobabeb (Fig. 100), also displays faint traces of cross-stratification. Elsewhere in the valley sector, the Gobabeb Gravels form a thin layer on the bedrock or on Homeb Silts. The clasts in these exposures are commonly concentrated on the downstream side of small topographic highs such as those formed in the granites near Gobabeb (Fig. 98).

On many terrace exposures in the lower canyon - valley sector, the Gobabeb Gravels are underlain by a thin, but conspicuous vesicular carbonate layer (Fig. 104) which indicates the development of a stable lag gravel surface (Yaalon, 1974; pers. comm., 1980).

#### 2.10.4 Mode of origin

The distribution of Gobabeb Gravels, as well as the composition of the clast assemblage, points to a fluvial origin for these deposits; this was assumed earlier by Korn and Martin (1957). This contention is corroborated by the decrease in maximum clast size downstream from the Escarpment, a trend that is also evident in the modern Kuiseb River and the older Oswater and Karpfenkliff Conglomerate Formations. Similarly, imbrication of the larger clasts in the Gobabeb Gravels is comparable with that reported from other fluvial settings (Harms *et al.*, 1975; Blatt *et al.*, 1980, p. 123, amongst others).

Rare occurrences of stratified, consolidated gravels in the canyon sector also indicate a fluvial origin for the Gobabeb Formation. The cross-bedded conglomeratic strata exposed at Aub are reminiscent of the stratification developed in transverse gravel bars of a braided stream (Harms *et al.*, 1975; Hein and Walker, 1977). The preferential deposition of Gobabeb Gravels on the downstream side of the small topographic highs implies a relatively shallow, probably braided, fluvial depositional environment in a broader, higher-lying Kuiseb River than exists at present (Fig. 100, longitudinal profile). The subsequent development of stable lag gravel surfaces, as evidenced by the underlying vesicular carbonate layers, was effected by subaerial weathering processes.

Within the lower canyon - upper valley reach, Gobabeb Gravels overlie Homeb Silts and can be traced from elevations c. 30 m to several metres above the present river bed and roughly parallel to the modern course (Fig. 100, longitudinal profile). In that reach, therefore, the Gobabeb Gravels must have been deposited as the Kuiseb River re-incised through sediments of the previous aggradational cycle, remnants of which are preserved today as the Homeb Silts. Similarly, the development of terrace deposits derived from washes rising in the gramadullas occurred during this re-excavation phase, the elevation of the Kuiseb bed forming a local base level to which these tributaries were graded. Thus the Gobabeb Gravel Formation differs from the Homeb, Oswater, Karpfenkliff and Tsondab Formations which are comparatively thick, aggradational successions.

The relatively fresh appearance, angularity and abundance of the locally-derived, mica-quartz schist fragments in the terrace deposits suggest that arid conditions prevailed in the Lower Kuiseb Valley during the re-incision phase when the Gobabeb Gravels were laid down. This assumption is also supported by the abundance of dune-derived sands in the mixed quartz sand assemblage of the Gobabeb Gravel deposits in the delta area. The development of desert varnish on carbonate-rich clasts derived from the Oswater Conglomerate and Homeb Silts, as well as the preservation of calcified urani-

um-bearing, gritty conglomerates and gypsiferous rudite and arenite fragments farther west, also indicate a predominance of arid conditions during, and subsequent to, the deposition of the Gobabeb Gravels in the Lower Kuiseb Valley.

The absence of dune sand intercalations in the Gobabeb Gravel succession is ascribed to the degradational mode of emplacement of these fluvial deposits. The occurrence of dune-derived quartz grains in Gobabeb Gravels exposed in the Kuiseb Delta sector implies fluvial erosion of dunes situated on the (?) southern bank of the Kuiseb River. This suggestion, however, should be adopted with caution because the Homeb succession includes typical dune- and Kuiseb River-derived quartz grains in some arenaceous beds (Section 2.8.3) which may have been introduced into the Gobabeb Gravel deposits during the ensuing erosional phase. Although these arguments for an association between the Lower Kuiseb River and dunes derived from the main Namib Sand Sea appear equivocal, other field evidence (cited earlier) implies the prevalence of arid conditions in the Central Namib tract during the deposition of the Gobabeb Gravels.

The apparent lack of Gobabeb Gravels along the Kuiseb river in the Bubuses - Ururas reach is attributed to a more southerly position of the river's course at that time. The presence of Gobabeb-type gravels and subterranean water in some U- and J-line boreholes (Bg21900, Bg21612), as well as the interpretation of a seismic investigation by Van Zijl (1970), suggests that the Kuiseb course ran west of Klipneus and south of the */Hai-gowab* metaquartzite ridge (Fig. 100). An observation in favour of this argument is the presence of small slabs of greyish metaquartzite, which forms the */Hai-gowab* ridge, in the delta terrace gravels. The subsequent northward shift of the Kuiseb course to its present position may have been effected by a general northerly migration of dunes from the main Namib Sand Sea.

#### 2.10.5 Age and correlation

The Gobabeb gravels partly truncate the Homeb Silts which have been dated by Vogel (1982) at c. 23 000 - c. 19 000 BP (upper Late Pleistocene). A sample of carbonate from the "12 m terrace" at Homeb gave a <sup>14</sup>C date of c. 9 600 BP (Vogel, 1982). In the extreme-arid environment of the Central Namib, the development of a vesicular carbonate layer under a lag of Gobabeb Gravels probably indicates landform stability over a period of several thousand years (Yaalon, pers. comm., 1980). The deposition of the Gobabeb Gravels would thus have occurred prior to the Early Holocene. The presence of rolled MSA artefacts in some gravel exposures also speaks for a Late - End

Pleistocene age for the Gobabeb Gravels. This agrees well with Korn and Martin's (1957) estimate of an End Pleistocene age for the "non-calcified gravels accompanying all the rivers as low terraces" (p. 17).

Korn and Martin (1957) suggested that low-lying, End Pleistocene gravel deposits can be found in almost all the rivers in SWA/Namibia. Unconsolidated gravels, containing rolled MSA artefacts, cover a well-developed terrace in the lowermost, coastal reaches of the Swakop and Omaruru Rivers (Korn and Martin, 1957). Farther north, on the Skeleton Coast, uncemented gravels form the uppermost section of the thick sediment wedge comprising the Unjab "delta" (Fig. 97). The Lower Hoarusib River contains a good example of Gobabeb-type gravels which overlie fine-grained silty sediments correlated with the Homeb Silts (Fig. 105).

This correlation of the Gobabeb Gravels with other similar deposits in the Namib emphasises the probability of a regional

control on the hydrological regimes of the larger, westward-draining rivers during the Pleistocene.

### 2.11 Khommabes Carbonate Member of the Sossus Sand Formation

#### 2.11.1 General

A number of locally developed carbonate deposits, commonly associated with cemented to unconsolidated dune-derived arenites, crop out in the interdunes of the main Namib Sand Sea within the study area (Fig. 106). The field relationships suggest that these carbonate deposits accumulated at intervals during the development of the main Namib Sand Sea, which appears to have originated in the Pliocene and continued through the Pleistocene to the present day (Martin, 1950, 1973; Stocken, 1978; Ward *et al.*, 1983). The dunes and associated arenaceous deposits of the main Namib Sand Sea constitute the Sossus Sand Formation (SACS, 1980). It is proposed here that the scattered carbonate deposits found in the main Namib Sand Sea are a facies of the Sossus Sand Formation, and they have therefore been accorded the formal status of Khommabes Carbonate Member.

The geographical name of this member is taken from the Topnaar locality of *!Khomabes* which comprises the vegetated dune hummocks, colonised mainly by *Acanthosicyos horrida* (*!nara*), fringing the southern margin of the type locality exposure (Fig. 106). This locality, at about 23°32'S and 15°00'E, is c. 6 km north-west of Gobabeb and c. 1.5 km south of the Kuiseb River (Fig. 107). A simplified plan of the type locality of the Khommabes Carbonate Member is displayed on the general distribution map, Fig. 107.

The Khommabes Carbonate sediments, although not deposited by the Kuiseb River, form an integral part of the Late Cenozoic record in the Central Namib. In this report, the Khommabes Carbonate Member is discussed last, which is not a reflection of their stratigraphic context but of their origin (Fig. B.1; Table 2).

#### 2.11.2 Distribution and thickness

Deposits identified as Khommabes Carbonate are scattered widely through the interdune areas of the northern sector of the main Namib Sand Sea (Figs. B.1, 107). These deposits are associated with present day topographic depressions (Fig. 108) which, under favourable rainfall conditions, hold water for short periods.

In the eastern part of the study area, scattered shallow depressions have developed in the Kamberg Calcrete duricrusts capping deposits of the Karpfenkliff and Tsondab Formations (Fig. 109). A wide range of Stone Age artefacts, from Early Stone Age (ESA) to Later Stone Age (LSA), are commonly associated with these depressions which Marker (1982) referred to as dolines. Therefore, these depressions have been in existence since at least the Middle Pleistocene and are thus considered to be time equivalents of the Khommabes Carbonate deposits preserved farther west (Fig. 107).

Within the limits of the main Namib Sand Sea, the Khommabes Carbonate deposits rest on reddish arenites of the Tsondab Formation or on schistose or granitoid bedrock. In the western area, south of about Swartbank, Khommabes deposits are patchily preserved on the margins of macro-fractures developed in the Tsondab Sandstone (Fig. 110). Some of these western sites appear to be related to the Tsondab drainage system. The Khommabes Carbonate deposits are mostly less than 2 m thick.

### 2.11.3 Lithology and structure

The Khommabes deposits consist chiefly of pale greyish carbonate (Fig. 108) which usually contains scattered detrital, sand-sized quartz grains and minor mica flakes. XRD analyses of samples from Khommabes, and an exposure c. 8 km south-west of the type locality (Fig. 107), reveal that calcium carbonate is the major component, although the detrital quartz sand content can amount to 30 per cent. At several localities in the western sector, the carbonate deposits are not only greyish in colour, but also include yellowish and black varieties that are, in places, silty.

Calcified casts of plant material (up to 100 per cent calcium carbonate) are commonly found in the Khommabes Carbonate deposits. In particular, reed stem material of a *Phragmites* sp. (C.J. Ward, pers. comm., 1979/83), is well preserved in mostly <0.25 m lengths at some exposures (Fig. 111). Gastropod shells, tentatively identified as *Succinia* sp. (Theron and Oberholzer, pers. comm., 1979), were noted in calcified vegetation associated with a small carbonate exposure c. 1.5 km south of Gobabeb (Fig. 107). Snail shells were also recovered from several carbonate deposits on the margins of macro-fractures in the Tsondab Sandstone exposed in the western part of the study area. These specimens were identified as *Melanoides tuberculata*, *Tomichia* sp., cf. *T. ventricosa*, *Bulinus* sp. and *Biomphalaria pfeifferi* (C. Appleton, written comm., 1986).

Reddish, quartzose arenites of the Sossus Sand Formation are preserved commonly on the margins of the Khommabes Carbonate deposits and, at several localities, exhibit a mottled, yellowish colour. At Khommabes, mottled sands include a c. 0.1 m thick layer of black-stained sands which occurs on the southern and south-eastern flank of the exposure. Large-scale cross-stratification, with the inclined strata dipping northwards, is evident in some arenite exposures (Figs. 107, 112). At the type locality, intricate biogenic structures cut across the internal stratification of the quartz arenites exposed on the north-western margin of the carbonate deposit (Figs. 107, 112). Pedotubules, which closely resemble the calcified counterpart of roots of the Namib endemic, *Acanthosicyos horrida* (Fig. 113), were noted in the arenites flanking the southern margin of the carbonate deposit at Khommabes (Fig. 107).

Mammalian fossils have been found in several Khommabes Carbonate deposits. On the southern margin of the type locality, 810m (pers. comm. 1982/83) found oryx/gemsbok (*Oryx gazella*) bones. The oryx, an extant antelope species, inhabits the drier regions of southern Africa, including the Namib Desert. Fossil remains of large mammals, including the extinct *Elephas recki*, were recovered from a carbonate deposit referred to as Namib IV, c. 8 km south from Harubes on the Kuiseb River (Shackley, 1980; Fig. 107). Stone Age artefacts were noted in the immediate vicinity of many of the Khommabes Carbonate deposits. A broad spectrum of typologies is represented, including:

- (i) those typical of the Early Stone Age (ESA), for example, the large hand-axes and cleavers at the Namib IV site (Shackley, 1980);
- (ii) blades and points typical of the Middle Stone Age (MSA), commonly found near Khommabes Carbonate deposits in the western sector. Korn and Martin (1957) also reported the widespread occurrence of MSA artefacts in the "driest parts of the Namib Desert" (p. 19);
- (iii) Later Stone Age (LSA) artefacts, e.g., at the Khommabes type locality (Clark, pers. comm., 1983);

As mentioned earlier, a mixed Stone Age artefact assemblage, ranging from ESA to LSA, is commonly associated with the pans (or dolines) in the Kamberg Calcrete in the eastern part of the study area (Shackley, 1985).

### 2.11.4 Mode of origin

The combination of occurrence at isolated sites, carbonate composition, calcified vegetation, notably reed (*Phragmites* sp.) material, and the presence of gastropods indicates that the Khommabes Carbonates are pan deposits, which are best described as lacustrine-type carbonates (Yaalon, pers. comm., 1980; Fig. 8.1). The relationship between the Khommabes Carbonate Member and the Sossus Sand Formation is thus a geologically young analogue of the Zebra Pan Carbonate Member in the Tsondab Sandstone Formation (Table 2; Section 2.2).

A number of contemporary perennial and temporary water bodies in the Namib are characterised by the presence of the reed, *Phragmites australis*. Similarly, the extensive reed beds developed on the coastal flats and adjacent dunes west and south of the Kuiseb Delta are maintained by the high water table of the Lower Kuiseb River. The ability of *P. australis* to rapidly colonise sites with sufficient moisture was demonstrated along the Lower Kuiseb River where reeds grew at temporary leaks in the Water Affairs pipeline between Ituseb and Rooibank (Fig. B.1). The occurrence, therefore, of calcified reed stalk and leaf material in the Khommabes Carbonate deposits indicates at least temporary standing water in locally restricted depressions.

Within the present-day Namib, rare pools of water usually contain algae and also support a fringe of macrophytes, such as *P. australis* (Fig. 114). At such sites, the basal parts of those reeds growing in the water are commonly encrusted by an alga(e) (Fig. 114). Calcification can be effected by such organisms (Street-Perrott, pers. comm., 1983), therefore the length of the calcified reed stalks preserved in the Khommabes deposits may represent the former depth of standing water at those sites. The presence of *Biomphalaria pfeifferi*, *Bulinus* sp., *Melanoides tuberculata* and *Tomichia* sp. in the Khommabes Carbonate deposits likewise points to the existence of fresh to brackish water pans in former times. In contrast, *Succinia* snails are more commonly associated with vegetation growing in moist settings than with open water sites (Street-Perrott, pers. comm., 1983).

The arenites associated with the Khommabes deposits are dune-derived, as evidenced by the sand grain characteristics and large-scale cross-stratification (cf. Bigarella, 1972; McKee, 1979; Fig. 22). Their terrestrial origin is further indicated by the intricate biogenic structures, which resemble termitaria or ant nests constructed under plants in the modern Namib Sand Sea, and the presence of *Acanthosicyos horrida* root casts. The occurrence of aeolian dunes, and related biota, confirms the predominance of arid conditions in the Central Namib during Khommabes times. The mottling of the dune sands was caused by the mobilisation and accumulation of iron and manganese compounds during incipient pedogenesis, a feature common in subterranean zones that are periodically saturated with water (MacVicar *et al.*, 1977, reprinted 1981). Such conditions would be expected on the margins of temporary pans in an otherwise arid environment.

These interpretations are not necessarily in conflict with the occurrence of large mammalian fossils, including *E. recki*, in several Khommabes deposits. Whereas Shackley (1980) postulated the existence of bushveld savanna in the Central Namib during Khommabes times to account for the Namib IV fossil assemblage, Ward *et al.*, (1983) suggested that a predominantly arid environment prevailed at that time. Their re-assessment was based on the presence of a palaeo-dune rim on the north-western side of the Khommabes deposit at Namib IV and the distribution of several animal species, including the elephant (*Loxodonta africana*), within the present day extreme-arid Northern Namib Desert (Ward *et al.*, 1983).

The Khommabes pan deposits therefore originated in localised water bodies that probably formed during limited periods of higher rainfall in an otherwise arid environment of the Central Namib. This contention is strengthened by the apparent close association between Khommabes Carbonate deposits and Stone Age assemblages. The wide range of typologies implies intermittently favourable conditions (higher rainfall) during the accumulation of the Sossus Sand Formation in the Central Namib.

#### 2.11.5 Age and correlation

The occurrence of Stone Age artefacts, ranging from ESA to LSA, in the immediate vicinity of a number of Khommabes Carbonate deposits suggests that these pans were sites of episodic occupation from at least the Middle Pleistocene onwards. The Khommabes Carbonate, therefore, was probably deposited at any humid interval during the arid Pleistocene when conditions in the Central Namib favoured pan formation.

The oldest dated Khommabes deposit is at the Namib IV site (Fig. 107); *Elephas recki* remains point to an age between 700 000 and 400 000 BP. This Middle Pleistocene age is supported by the ESA artefacts in the immediate vicinity (Shackley, 1980). In contrast, the LSA assemblages at the type locality, Khommabes, (Clark, pers. comm., 1983) appear to corroborate the <sup>14</sup>C dates of about 22 000 - 20 000 BP and 32 000 - 27 000 BP (Late Pleistocene) obtained for calcified reed casts (Vogel and Visser, 1981). A similar Late Pleistocene age (c. 21 000 BP) was also obtained by Vogel and Visser (1981) for the small palaeo-pan exposure south of Gobabeb. The occurrence of MSA artefacts in the vicinity of several Khommabes deposits in the western sector points towards an age intermediate between the Middle and Late Pleistocene estimations given above. Korn and Martin (1957) postulated a wetter phase during the MSA to account for the distribution of that typology in the Namib Desert.

Deposits similar to the Khommabes Carbonate have been noted elsewhere in the main Namib Sand Sea (Table B.3). A pan carbonate occurring at Narabeb, c. 40 km south of Gobabeb, has been dated between 240 000 and 210 000 BP using the U/Th method (Selby *et al.*, 1979). Early Stone Age artefacts were also found in the vicinity of this site (Seely and Sandelowsky, 1974). The well-preserved condition of the Narabeb carbonate led Selby *et al.* (1979) to suggest that arid conditions have dominated the Central Namib for the last 200 000 years. In the Southern Namib, a fossil pan deposit is exposed near the endpoint of the Koigab River, north-east of Lüderitz (Fig. 115). The northern rim of the Koigab deposit consists mainly of calcium carbonate containing abundant reed (*Phragmites* sp.) casts, whereas the central, and lower, part of the palaeo-pan is composed chiefly of dolomite. In addition, presumed LSA implements form a surface scatter on the northern side of the Koigab exposure.

In summary, therefore, the Khommabes-type deposits reflect intermittent periods of pan formation that accompanied the development of the main Namib Sand Sea, i.e., the Sossus Sand Formation. These pan or lacustrine carbonate deposits were probably formed after episodic, high rainfall events in the otherwise arid Central and Southern Namib during the Quaternary.

### 3. SUMMARY

#### 3.1 General

The earlier geological/geomorphological frameworks proposed for the accumulation of the Cenozoic deposits in the

Kuiseb Valley west of the Escarpment have been updated by the recognition of 10 principal lithostratigraphic units comprising this succession. The palaeo-environmental interpretations proposed for these units, as well as their suggested geochronologic sequence (Ward 1984b), are summarised in Table 6. Five major episodes have been distinguished in the depositional history of the Cenozoic cover in the study area (Table 6):

- (v) Namib Desert phase;
- (iv) Pedogenic phase;
- (iii) Karpfenkliff fluvial phase;
- (ii) Proto-Namib Desert phase;
- (i) Post-Gondwana erosion phase.

The development of the Kuiseb Valley west of the Escarpment is summarised below in relation to these regional episodes which have influenced a large part of the Namib tract.

#### 3.2 Post-Gondwana Erosion Phase

The Great Escarpment was formed largely by headward erosion following the break-up of West Gondwana in the Early Cretaceous (Martin, 1973, 1975; Dingle and Scrutton, 1974; Simpson, 1977). An extensive pediplain, the *NAMIB UNCONFORMITY SURFACE*, was consequently cut across predominantly Late Precambrian bedrock in the process of grading the coastal tract down to the South Atlantic Ocean (Martin, 1973, 1975; Ollier, 1977). This surface forms the fundamental datum of the Cenozoic succession in the Central Namib tract.

The c. 4 km-thick wedge of Upper Cretaceous sediments offshore in the Walvis Basin and the substantially lower rates in offshore sedimentation during the Tertiary (Dingle *et al.*, 1983, p. 223-225, 297), suggest that the Namib Unconformity Surface had been established by the end of the Cretaceous or the earliest Tertiary. A wide bedrock depression on the Namib Unconformity Surface between the Naus-gomab/Chausib area, near the base of the Escarpment, and about the Barrowberg/Gomkaeb vicinity (Fig. B.1), demarcated a proto-Kuiseb Valley. The south-westerly orientation of this ancestral valley may have been controlled partly by the trends of the Late Palaeozoic drainage systems which appear to have shaped the Nausgomab Valley and, by inference, part of the Kuiseb Valley (Martin, 1975).

#### 3.3 Proto-Namib Desert Phase

The predominantly arenaceous and subordinate rudaceous and carbonate deposits of the *TSONDAB SANDSTONE FORMATION* are the oldest surficial deposits on the Namib Unconformity Surface. Six facies, designated A - F, were recognised in the Tsondab succession in the study area. In Table 6, Facies A - F are presented in alphabetical order, which does not necessarily reflect their depositional sequence, and cognisance must be taken of lateral facies relationships. Arid conditions prevailed throughout the accumulation of these sediments, a period which probably spanned most of the Palaeogene (Tables 2, 6).

The rudaceous regolith (or skeletal lithosol) deposits forming Facies A have been recognised as the Gomkaeb Basal Breccia Member of the Tsondab Formation. The locally restricted Facies B deposits are considered to be colluvial material deposited on a small alluvial fan derived from the Barrowberg (Fig. B.1). The arenaceous sediments of Facies C and D were deposited as desert dunes and sand sheets, under a dominant southerly wind regime, to the south, west and north of the proto-Kuiseb Valley. The proto-Kuiseb Valley was filled chiefly by arenaceous sediments (Facies E) provided by ephemeral, low-energy streams draining the Escarpment region. These

TABLE 6: Summary of the inferred palaeo-environments and processes involved in the accumulation of the Cenozoic succession in the Kuiseb Valley west of the Escarpment.

TIME SPAN (not to scale)	PRINCIPAL LITHOSTRATIGRAPHIC UNITS	INTERPRETATION	MAJOR EVENTS
QUATERNARY	<p>Kuiseb River alluvium - - - - -</p> <p>Sossus Sand Formation - - - - - including</p> <p>Gobabeb Gravel Formation - - - - - Khammabes Carbonate Member - - - - -</p> <p>Awa-gamieb muds - - - - - Homieb Silt Formation - - - - -</p> <p>Hudaob Tufa Formation - - - - -</p> <p>Oswater Conglomerate Formation - - - - -</p>	<ul style="list-style-type: none"> <li>Ephemeral, braided river; modern, incised Kuiseb drainage system.</li> <li>Desert dunes and sand sheets of the main Namib Sand Sea; S-SW quadrant wind regime dominant; originated about Late-End Neogene.</li> <li>Ephemeral, shallow, braided river; reseeded gravels during degradational phase.</li> <li>Pans; formed intermittently during the accumulation of Sossus Sand Formation.</li> <li>Early Kuiseb Delta - coastal plain with littoral pans and aeolian dunes.</li> <li>Fluvial flood deposits of early Kuiseb River; 2nd aggradational phase.</li> <li>Calcium carbonate precipitation at groundwater seepage sites.</li> </ul>	<p>Namib Desert Phase</p>
NEOGENE	<p>Pliocene</p> <p>Kamberg Calcrete Formation - - - - -</p> <p>Rookop gravels - - - - -</p> <p>Karpfenkliff Conglomerate Formation - - - - -</p>	<p><i>The deep incision by the Kuiseb River and its major tributaries west of the Escarpment initiated by epeirogenic uplift</i></p> <ul style="list-style-type: none"> <li>Calcrete pedogenesis; semi-arid conditions and landform stability.</li> </ul>	<p>Pedogenic Phase</p>
TERTIARY	<p>Miocene</p> <p>Tsondab Sandstone Formation - - - - - Facies F - - - - - (Zebra Pan Carbonate Member) Facies E - - - - - Facies D - - - - - Facies C - - - - - Facies B - - - - - Facies A - - - - - (Gomkoeb Basal Breccia Member)</p>	<ul style="list-style-type: none"> <li>Littoral beach gravels deposited under warm-water marine conditions.</li> <li>Alluvial fans - braided streams in proto-Kuiseb and -Gaub Valleys; First record of well-developed drainage system west of the Escarpment; Koedoe River breccia represents talus material reworked into small alluvial fans.</li> <li><i>Change from desert to more mesic, semi-arid conditions.</i></li> <li>Pans; formed during accumulation of arenaceous facies C, D, E.</li> </ul>	<p>Karpfenkliff Fluvial Phase</p>
PALAEOGENE	<p>UNCONFORMITY</p>	<p>? Onset of terrestrial sedimentation west of the Escarpment.</p> <p>Proto-Kuiseb Valley - wide, shallow bedrock depression trending NE-SW from Nausgombab/Chausieb area to Barrowberg - Gomkoeb vicinity</p>	<p>Proto-Namib Palaeo-desert Phase</p>

streams probably did not reach the Atlantic Ocean. Wetter intervals during the Palaeogene desert phase rendered possible the formation of pans, a record of which is preserved today by the distinctive deposits identified as the Zebra Pan Carbonate Member (Facies F) of the Tsondab Formation.

Significantly, the proto-Namib desert phase preceded the full establishment of the cold-water Benguela Current System which originated in the Late Miocene (Siesser, 1978, 1980). These Palaeogene desert conditions may have been influenced by an early South Atlantic anticyclonic system, as evidenced by the inferred palaeo-wind regime, and the location of the Namib tract on the south-western, rain-shadow side of the sub-continent. In addition, a southerly quadrant wind regime is likely to have been instrumental in moving inland arenaceous sediments from the continental shelf which was exposed during the Oligocene regression (Dingle *et al.*, 1983, p. 313).

### 3.4 Karpfenkliff Fluvial Phase

The proto-Namib desert phase was terminated, probably in the Miocene, by a climatic change to semi-arid, summer rainfall conditions which promoted the deposition of rudaceous sediments comprising the *KARPFENKLIFF CONGLOMERATE FORMATION*. Additional evidence for high rainfall conditions in the Central Namib during Karpfenkliff times is provided by the *Koedoe River breccia* facies, which is mainly resedimented talus material derived from local topographic highs. Furthermore, the planation of the Tsondab Sandstone on the interfluvies and in the extreme western part of the study area is an indication of erosion and re-distribution by increased precipitation within the Namib tract.

The Karpfenkliff sediments were deposited in large alluvial fans that thinned downslope, away from the foot of the Escarpment, in the wide, unconfined proto-Kuiseb and -Gaub Valleys. The rudaceous deposits appear to have been distributed and reworked by braided, probably ephemeral stream systems. Considerable erosion of the Escarpment is inferred from the assemblage of resistant clast types which is dominated by Late Precambrian metaquartzite and vein quartz as well as Etjo Formation quartzite. High-velocity flow conditions during the emplacement of the Karpfenkliff deposits are indicated by the rounded to well-rounded shape of the clasts and the abundance of crescentic percussion marks.

The *Rooikop Gravels* are marine deposits, the basal remnants of which were laid down during a high stand of sea level in the Miocene. Thus the Rooikop gravels may be partly contemporaneous with the Karpfenkliff sediments, although the different elevations and presence of *Donax rogersi* also points to their deposition in the Late Pliocene and Early Pleistocene (Pether, 1986).

### 3.5 Pedogenic Phase

The Karpfenkliff fluvial phase partly overlapped with, and was followed by, a period of landform stability and semi-arid conditions conducive to the widespread development of pedogenic calcretes. These palaeosols constitute the *KAMBERG CALCRETE FORMATION* and are dated provisionally to the end of the Miocene. The mature calcrete duricrusts appear to have formed over a period of at least several hundred thousand years, during which time summer rainfall was probably in the order of 350 - 450 mm/yr (Yaalon and Ward, 1982). The Kamberg calcretes are developed in the uppermost part of the Tsondab Sandstone and Karpfenkliff Conglomerate deposits, particularly in the eastern sector of the study area. These duricrusts thus closely followed the surface of

the early landscape prior to the deep incision by the Kuiseb drainage system west of the Escarpment and are an important stratigraphic marker in the Cenozoic succession of the Central Namib.

### 3.6 Namib Desert Phase

The full establishment of the Benguela Current and its associated cold-water upwelling system in the Late Miocene has been instrumental in promoting the development of the current Namib Desert regime (Siesser, 1978, 1980; Tankard and Rogers, 1978; Tankard *et al.*, 1982, p. 453-454; Dingle *et al.*, 1983, p. 309-316). This desert phase, which has led to the accumulation of the *Sossus Sand Formation*, thus dates from the Late, or the end of the Tertiary. This formation, whose deposits constitute the main Namib Sand Sea, appears to have had its origins in the Pliocene (Stocken, 1978; pers. comm., 1983) and has persisted through the Pleistocene to the present day. Epeirogenic uplift of the continent at about the end of the Tertiary initiated the deep incision of the Kuiseb drainage system west of the Escarpment (King, 1951, p. 193; Korn and Martin, 1957). The history of the incised Kuiseb drainage system has, therefore, been largely contemporaneous with the development of the modern Namib Desert regime.

The ancestral Kuiseb River and its major tributaries incised through the Kamberg Calcrete, and underlying Karpfenkliff Conglomerate and Tsondab Sandstone deposits, into bedrock. During this initial degradational (erosion) stage, metaquartzite, vein quartz and quartzite clasts occurring in the Kuiseb River were derived chiefly from the high-lying Karpfenkliff Conglomerate. The subsequent Late Cenozoic history of the Kuiseb drainage system within the Central Namib tract reflects several aggradational/degradational (erosion) cycles.

The first aggradational stage is dated provisionally to the Early to Middle Pleistocene, when the rudaceous and interbedded arenaceous sediments of the *OSWATER CONGLOMERATE FORMATION* were deposited. Ephemeral flow in the sediment-choked floor of the ancestral Kuiseb drainage system caused braiding of river channels and promoted the formation of a downstream-thickening sediment wedge. A greater river competency during Oswater times compared with that in the present Kuiseb drainage system is attributed to higher summer rainfall in the Escarpment and Khomas Hochland areas (Korn and Martin, 1957) and to the steeper gradients of the early river courses.

Aeolian dune deposits interbedded with fluvial sediments of the Oswater Conglomerate Formation provide the first record of an association between the incised Kuiseb drainage system and the main Namib Sand Sea. These palaeo-dunes, which crop out in the lower canyon - upper valley sector of the Kuiseb River, are found on the southern (left) bank only. The relict dune partly rimming the *Khommabes Carbonate (Member of the Sossus Formation)* pan deposit at the fossiliferous Namib IV site provides additional evidence for the occurrence of reddish dunes in the Central Namib tract south of the Kuiseb River during the Middle Pleistocene.

The north-westerly orientation of the Lower Kuiseb River downstream from Natab had been established at least by the onset of the aggradational phase in the Early to Middle Pleistocene. From the results of a seismic investigation in the western part of the study area (Van Zijl, 1970), it is speculated that, in Oswater times, the distal Kuiseb course extended from the Klein Klipneus/Klipneus area westwards to the northern half of Sandwich Harbour (Fig. B.1).

The diagenetic cementation of the Oswater Conglomerate deposits was completed prior to the commencement of the

second degradational (erosion) stage, when the Kuiseb River re-incised to some 30 - 50 m below the ancestral (Oswater) course in the Escarpment - canyon sector.

The second aggradational stage, which appears to have occurred in the Late Pleistocene, is represented by the unconsolidated micaceous sediments constituting the *HOME B SILT FORMATION*. Contrary to several arguments favouring a dune dam accumulation or a river endpoint setting for the origin of the Homeb Silts, these sediments were probably deposited during major flood events in protected embayments adjacent to the Lower Kuiseb River course. Although considerable volumes of water appear to have been discharged down the Kuiseb River in Homeb times, the source was on the Escarpment and interior plateau and the Central Namib remained arid. Reddish dune sands, typical of the main Namib Sand Sea, are incorporated in the Homeb deposits, proving the presence of dunes, probably along the southern margin of the Lower Kuiseb River, in the Late Pleistocene.

The  $^{14}\text{C}$  ages of 23 000 - 19 000 BP for the Homeb Silts (Vogel, 1982) do not fit well into the general picture since this period coincides approximately with the Last Glacial Maximum in the Southern Hemisphere which was a particularly arid phase (Sarnthein, 1978; Salinger, 1981; Deacon, 1983). The major flood events inferred for the emplacement of the Homeb Silts do not appear compatible with an arid phase.

The *AWA-GAMTEB MUDS* which flank the present Kuiseb Delta are interpreted as distal, coastal equivalents of the Homeb Silt deposits. The Awa-gamteb muds accumulated in an early Kuiseb Delta - coastal plain environment. Paleocoloured (crescentic?) dune deposits, similar to those in the coastal, north-western sector of the modern main Namib Sand Sea, are interbedded in the Awa-gamteb muds. Arid conditions during Awa-gamteb/Homeb times are also inferred from the abundance of salt and gypsum crystal ("desert rose") horizons in the muddy deposits. The distal course of the Kuiseb River had, therefore, attained its present position by Awa-gamteb times, i.e., a general northward shift of c. 30 km occurred between the Early to Middle and the Late Pleistocene.

The third degradational (erosion) stage was marked by the partial re-excavation of the Homeb Silt deposits and the concomitant deposition of fluvial sediments of the *GOBABEB GRAVEL FORMATION*. The presence of rolled Middle Stone Age (MSA) artefacts in the Gobabeb Gravel deposits in the western sector of the study area, and a preliminary  $^{14}\text{C}$  date of 9 600 BP (Vogel, 1982) of the vesicular carbonate developed under a stable lag of Gobabeb Gravels, implies a probable Late to Terminal Pleistocene age for this event. The principal clasts in the Gobabeb Gravels are highly rounded, but they have been derived from the Oswater and Karpfenkliff deposits and their degree of rounding does not attest to long fluvial transport in Late Pleistocene times. Arid conditions, as indicated by the development of gravel lags and the well-polished appearance of the Gobabeb Gravel clasts, prevailed within the Central Namib tract during this stage.

Subsequent to the deposition of the Gobabeb Gravels, the course of the Lower Kuiseb River appears to have been displaced slightly farther north in the Klipneus - Rooibank sector during the (?) Holocene (Fig. B.1). However, studies of the Holocene microfauna from the Central Namib tract suggest that the Lower Kuiseb River has been an effective barrier to the encroachment of linear dunes from the main Namib Sand Sea for at least the last 6 000 years (Brain and Brain, 1977).

Although arid conditions have prevailed in the Kuiseb Valley west of the Escarpment during the Late Cenozoic, short-lived wetter intervals have interrupted this Namib Desert

phase from at least the Middle Pleistocene onwards. Higher rainfall during these brief periods promoted the formation of pans which were utilised by early man (Early,

Middle and Later Stone Age typologies). A record of these pans is provided by the scattered carbonate deposits of the *KHOMMABES CARBONATE MEMBER OF THE SOSSUS SAND FORMATION*. At some sites, particularly within the Kuiseb Canyon, these moister periods led to the development of groundwater seeps where calcareous deposits of the *HUDAOB TUFA FORMATION* were commonly precipitated.

A southerly wind regime appears to have prevailed during the accumulation of the main Namib Sand Sea (Sossus Sand Formation). This direction is inferred from the orientation and junctions of the Pliocene Obib dunes in the Sperrgebiet, Southern Namib (Stocken, 1978) and the northward dipping strata in the dune remnants of Pliocene age near Lüderitz, Southern Namib (Stocken, Jamieson and S. Talbot, pers. comm., 1982). Likewise, the palaeo-dunes associated with the Early to Middle Pleistocene Oswater Conglomerate and the Late Pleistocene Khommabes Carbonate deposits in the Central Namib indicate the persistence of a southerly wind regime comparable to that of the present day.

The predominance of arid conditions, interrupted by short-lived, slightly more humid periods, in the Namib tract during the Late Cenozoic is supported by the palynological record in the Plio-Pleistocene offshore sedimentary sequence (Caratini and Tissot, 1982; Van Zinderen Bakker, 1984). The Namib Desert phase is, therefore, a fairly recent event in the Cenozoic history of the Kuiseb Valley, the present day manifestation of which is exemplified by the main Namib Sand Sea that incorporates all the principal dune types and the ephemeral character of the Kuiseb drainage system.

#### 4. CONCLUSIONS

Five principal conclusions can be drawn from the investigation of the Cenozoic succession in the Kuiseb Valley west of the Escarpment, viz.:

(i) the depositional history of the Cenozoic succession within the Kuiseb Valley is not unique but can be related to 5 major phases of development that affected a large part of the Namib;

(ii) the cold-water Benguela Current System, the full establishment of which dates from the Late Miocene, does not appear to be a prerequisite for arid conditions to prevail in the Namib tract, as has been suggested by recent workers. This deduction is borne out by the extensive Tsondeb Sandstone deposits, and similar sediments, which accumulated in the Namib tract during the Palaeogene;

(iii) an early forerunner of the present Kuiseb Valley was a wide bedrock depression that had formed by the end of the Cretaceous or the earliest Tertiary. This proto-Kuiseb Valley was filled initially, during the Palaeogene, by a fluvial facies of the Tsondeb Formation. Subsequently, the Karpfenkliff sediments were deposited in the proto-Kuiseb and Gaub Valleys during the Miocene, providing a record of the first well-developed Kuiseb/Gaub drainage system west of the Escarpment. However, these rudaceous sediments were laid down in an unconfined valley or on a braid plain and not in confined, deeply-incised channels characteristic of the contemporary Kuiseb drainage system;

(iv) the deep incision of the recent Kuiseb Valley took place at the end of the Tertiary; it was apparently initiated by epeirogenic uplift of the subcontinent. The subsequent Late Cenozoic elaboration of the Kuiseb drainage system, which

exhibits several aggradational and degradational cycles, reflects an overall, but fluctuating, decrease in hydrological competency from the Early - Middle Pleistocene (Oswater Conglomerate) through the Late Pleistocene (Homeb Silts/Awa-gamteb muds) and End Pleistocene (Gobabeb Gravels) to the present day. This trend parallels that proposed for the progressive aridification of the Namib tract during the Late Cenozoic (Korn and Martin, 1957; Soares Carvalho, 1961; Siesser, 1978, 1980; Tankard and Rogers, 1978; Tankard *et al.*, 1982, p. 453-454; Dingle *et al.*, 1983, p. 309-316);

(v) the first association between the Kuiseb River and the main Namib Sand Sea is recorded in the Early - Middle Pleistocene Oswater Conglomerate deposits that represent the initial aggradational stage in the incised Kuiseb drainage system. The subsequent Quaternary record reveals that the Kuiseb River has been maintained as the northern boundary of the main Namib Sand Sea, except in the distal reach where the course appears to have shifted c. 30 km northwards from about Sandwich Harbour (in Oswater times) to its present position. This displacement may have been caused primarily by the northward encroachment of dunes from the main Namib Sand Sea, which has accumulated under a dominant southerly quadrant wind regime and has been in existence since the Pliocene. The shift in the lower course was only possible because here the Kuiseb, which has experienced an ephemeral flow regime during most of the Quaternary, did not flow in a canyon but rather in a broad valley with low banks.

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## APPENDIX

TABLE B.1: Type and reference localities of the Cenozoic units in the Kuiseb Valley, Central Namib Desert.

UNIT	LAT. (S)	LONG. (E)	NOTES
Tsondab Sandstone Formation	23°55'	15°25'	Sandstone cliffs eastern side of Tsondab Vlei
Gomkaeb Basal Breccia Member (Tsondab Fm)	24°42½'	15°27'	Steep cliff on S side of Kuiseb Canyon at Gomkaeb
Zebra Pan Carbonate Member (Tsondab Fm)	23°34'	15°39'	c. 15 km SE of Zebra Pan water point, on S side of Kuiseb Canyon. Isolated knoll.
Karpfenkliff Conglomerate Formation	23°20'	15°45'	Carp Cliff mesa (Kuiseb Canyon look-out)
Koedoe River breccia facies (Karpfenkliff Fm)	23°19'	23°52'	Tributary of Koedoe River 3 km west of Schlesien farmhouse.
Rooikop gravels (informal unit)	23°00'	14°36'	Along water pipeline between railway and main Rooikop-Walvis Bay road, c. 10 km E of Walvis Bay
Kamberg Calcrete Formation	23°36½'	15°39'	Duricrust-capped mesa of Tsondab Sandstone c. 7 km SW of the Kamberg beacon
Oswater Conglomerate Formation	23°38'	15°08'	Conglomerate mesa with Water Affairs beacon DW 306 sited on it. Approx. 4 km downstream from the Oswater village
Hudaob Tufa Formation	23°42'	15°31'	Steep, left (SE) bank, tributary wash of Kuiseb, c. 70 km upstream from Gobabeb, in canyon
Homeb Silt Formation	23°38'–39'	15°11'–12'	Homeb campsite area, vicinity of DW 303 beacon, N bank of Kuiseb River.
Awa-gamteb muds (informal unit)	23°08'	14°31'	c. 2 km S of Water Affairs borehole Bg 1/77 on W edge of dune field.
Gobabeb Gravel Formation	23°34'	15°03'	Gravel-capped terrace E side of Gobabeb wash, immediately SE of Namib Research Institute
Khommabes Carbonate Member (Sossus Sand Fm)	23°32'	15°00'	Interdune valley, c. 6 km NW of Gobabeb and 1,5 km S of Kuiseb River

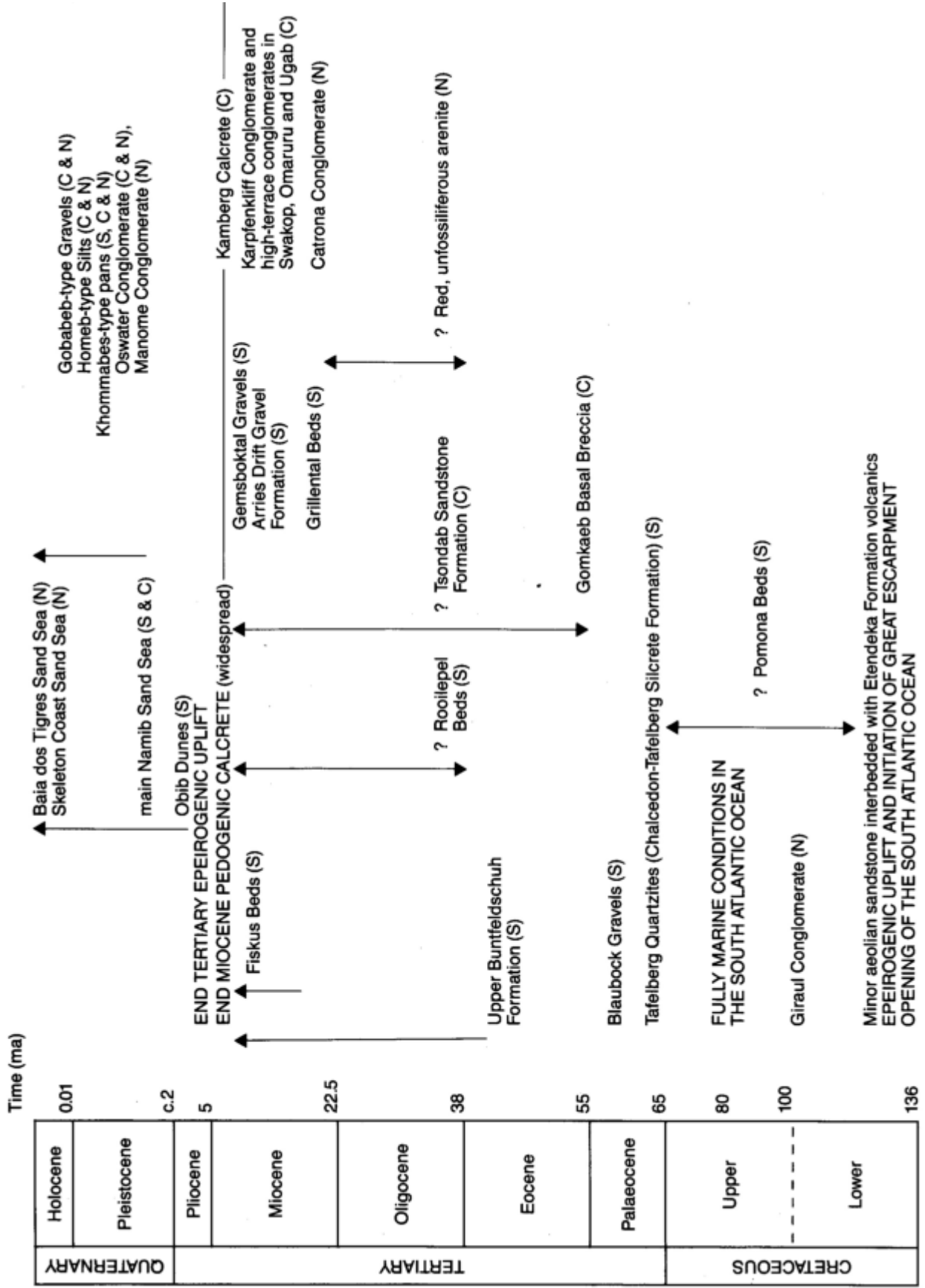
TABLE B.2: X-Ray powder diffraction analyses of selected samples (peak height percentages) from the Cenozoic succession in the Kuseib Valley west of the Escarpment.

Analyses undertaken by Dr. D. Bühmann, Dept. of Geology, University of Natal, Pietermaritzburg.

Rock type and Locality	Sample No.	Quartz %	Calcite %	Dolomite %	Salt %	Other %
<i>Tsondab Sandstone</i>						
Facies A, Carp Cliff	K151	52	25	18	—	5
Facies A, Kamberg Cliff	K191	66		34		
Facies C, Kamberg area	K212(b)	95				5
Facies C, Kamberg area	K217	96				4
Facies C (± indurated horizon)	K218	56	33	3		8
Facies C units interbedded with						
Facies E, Kamberg Cliff	K183	58			42(Na)	
Facies E, Kamberg Cliff	K186	59	1		40(Na)	
Facies E, Kamberg Cliff	K196	45			53(Na)	2
Facies E, Kamberg Cliff	K202	95				5
Facies E, Carp Cliff	K144	42	40	14		4
Facies E, Carp Cliff	K145	45	45			10
Facies E, Kamberg Cliff	K184	46	52			2
Facies E, Kamberg Cliff	K185	69	6	19	3	
Facies E, Kamberg Cliff	K197	44		50		6
Facies E, Kamberg Cliff	K203	62			36	2
Facies E, Kamberg Cliff	K236	75		17		8
Facies E, Kamberg Cliff	K237	62	17	21		
Facies E, Kamberg Cliff	K245	22	47	23	5	3
Facies F, Kamberg area	K221(a)		10	87		3
Facies F, Kamberg area	K221(b)		15	80		5
Facies F, Kamberg Cliff		6		85		9
<i>Karpenkliff Conglomerate</i>						
Arenite matrix	K148	56	44			
Arenite lens, Carp Cliff	K187	63	36			
Arenite lens, Kamberg Cliff	K188	38			66	6
Arenite lens, Kamberg Cliff	K208	65	32	2		1
<i>Kamberg Calcrete</i>						
Laminar crust, Kamberg	K230(b)	5	95			
Hardpan, Kamberg	K230(a)	16	84			
Nodules, Kamberg	K212(a)	66	30		4	
<i>Oswater Conglomerate</i>						
Palaeo-dune, Natab	K87	57	41			2
Arenaceous lens, DW 306	K91	8	92			
Arenite lens, WA 119	K117	66	32			2
Arenite lens, WA 111A	K140	54	46			
Arenaceous lens, Uspas Bridge	K392	14	86			
<i>Khommabes Carbonate</i>						
Palaeo-pan; south of Obab	K229	29	69			2
Calcified root, Khommabes	K478		100			
Calcified reed, Khommabes	K479	6	94			



TABLE B.3: Stratigraphical summary of Late Mesozoic-Cenozoic terrestrial sedimentation in the Namib.  
 NOTE: N = Northern regions of the Namib, S = Southern, C = Central (Modified from Ward *et al.*, 1983).



## FIGURES

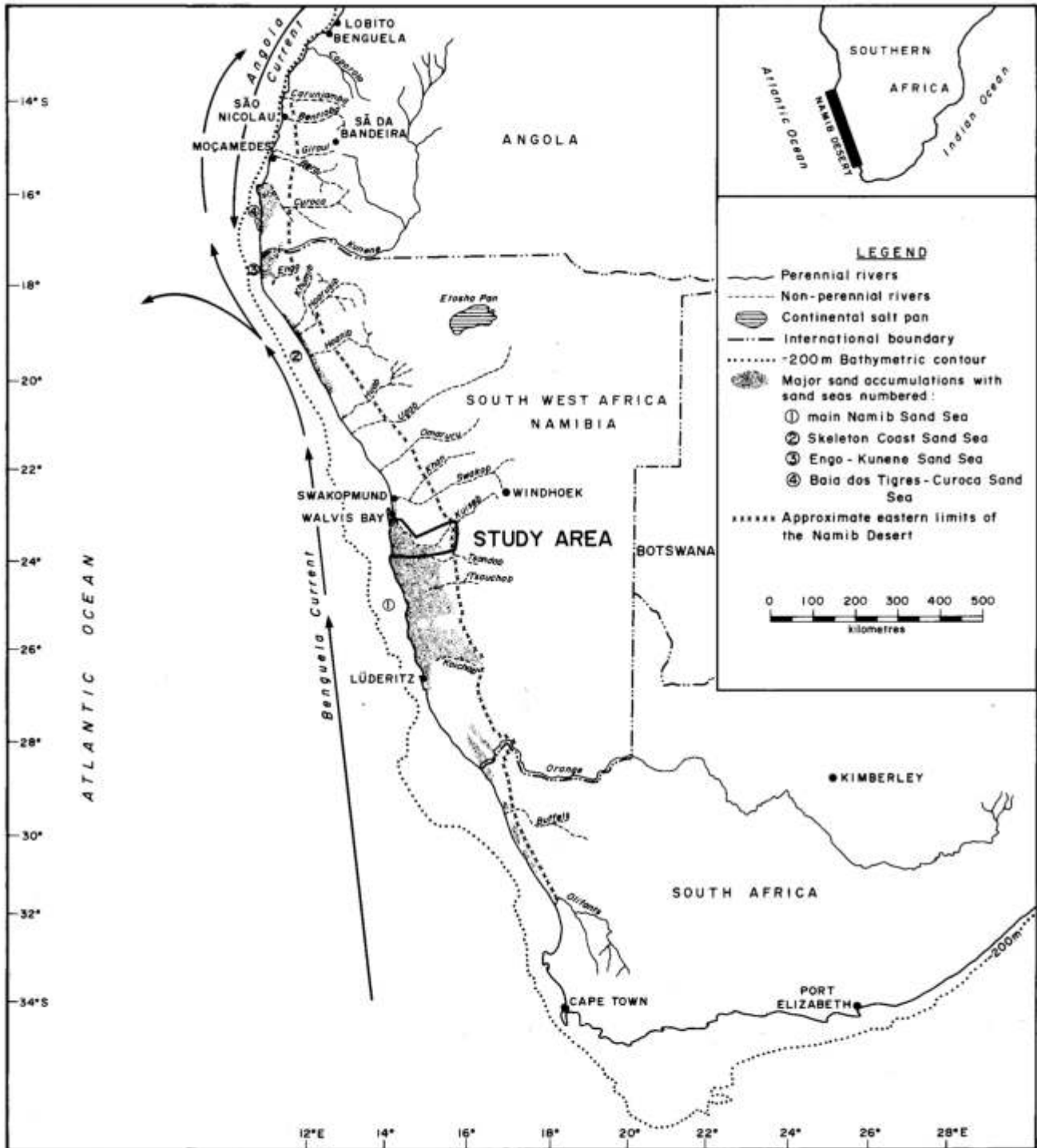


Figure 1: Locality map of the Namib Desert, south-western Africa. The study area encompasses the Kuseib drainage system west of the Escarpment (from Ward *et al.*, 1983).

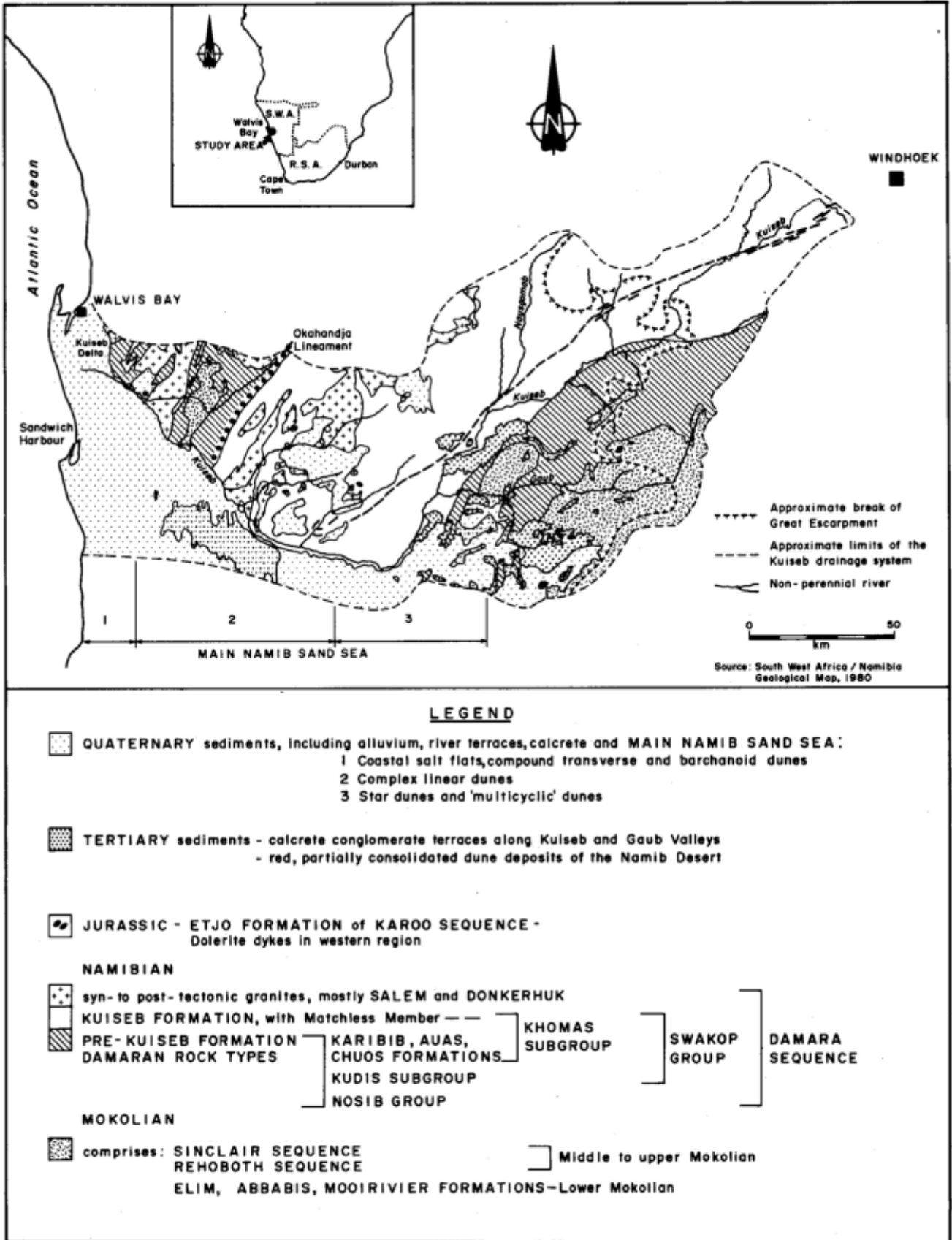


Figure 2: Simplified geological map of the Kuiseb drainage system (modified from the Geological map of S.W.A./Namibia, 1980).

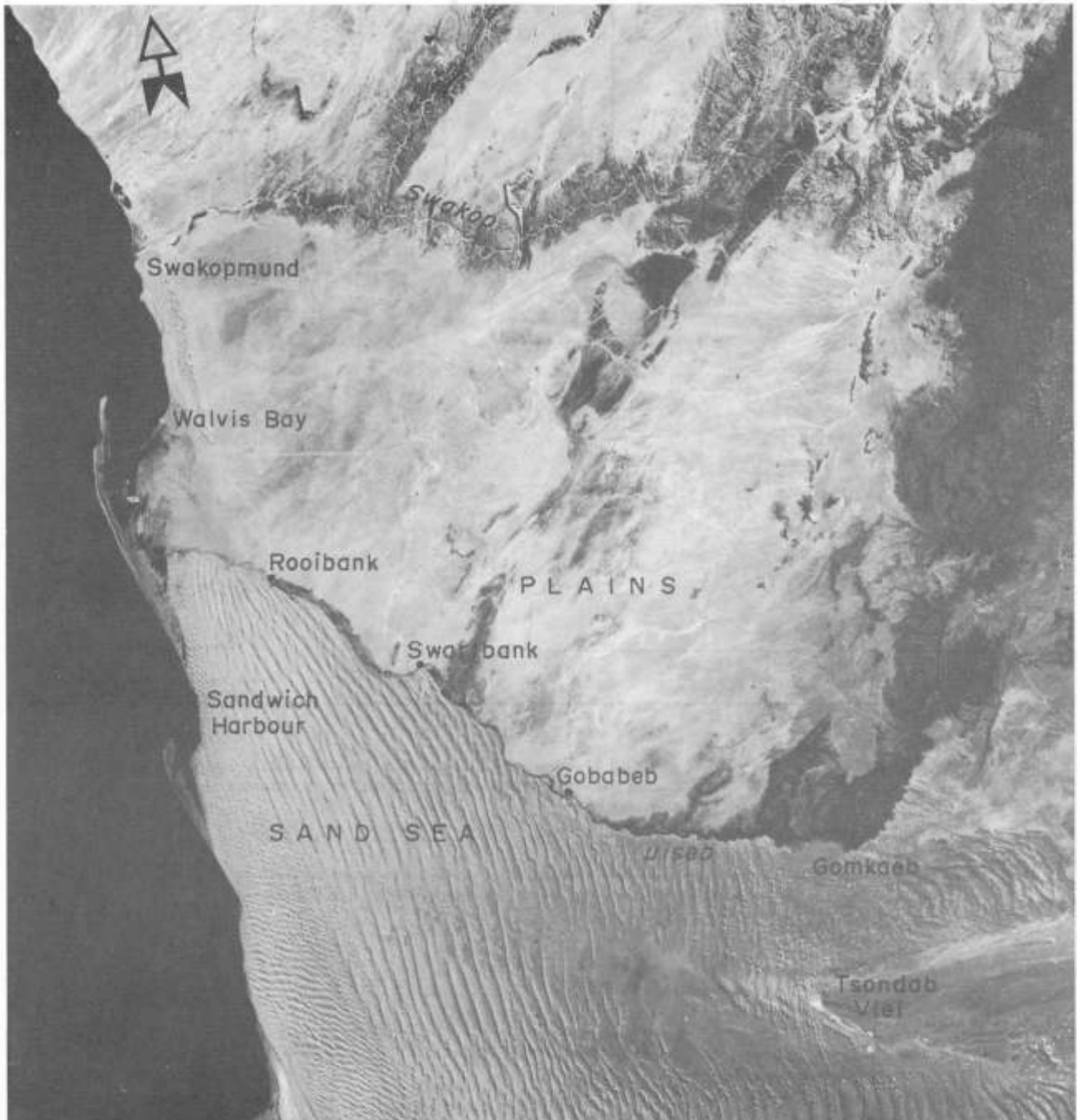


Figure 3: Satellite image of the Central Namib Desert. The Kuiseb River forms the northern boundary of the main Namib Sand Sea, except near the coast. Landsat 2, no. 2228708131, April 1981.





Figure 5: The Namib Unconformity Surface cut across inclined schists of the Late Precambrian Damara Sequence (Kuseb Formation) and overlain by c. 12 m of calcified Tsondab Formation deposits. Gomkaeb corner, Kuseb Canyon; people for scale.



Figure 6: Oblique aerial view south-westwards over the Kuseb canyon at Gomkaeb, illustrating the salient features of the Cenozoic geology. 1: Erosion surface cut across Damaran schists 2: Tertiary deposits pre-dating canyon incision. 3: Quaternary terrace deposits post-dating canyon incision. 4: Modern Kuseb River. 5: Dunes of the main Namib Sand Sea. (after Ward, 1982).

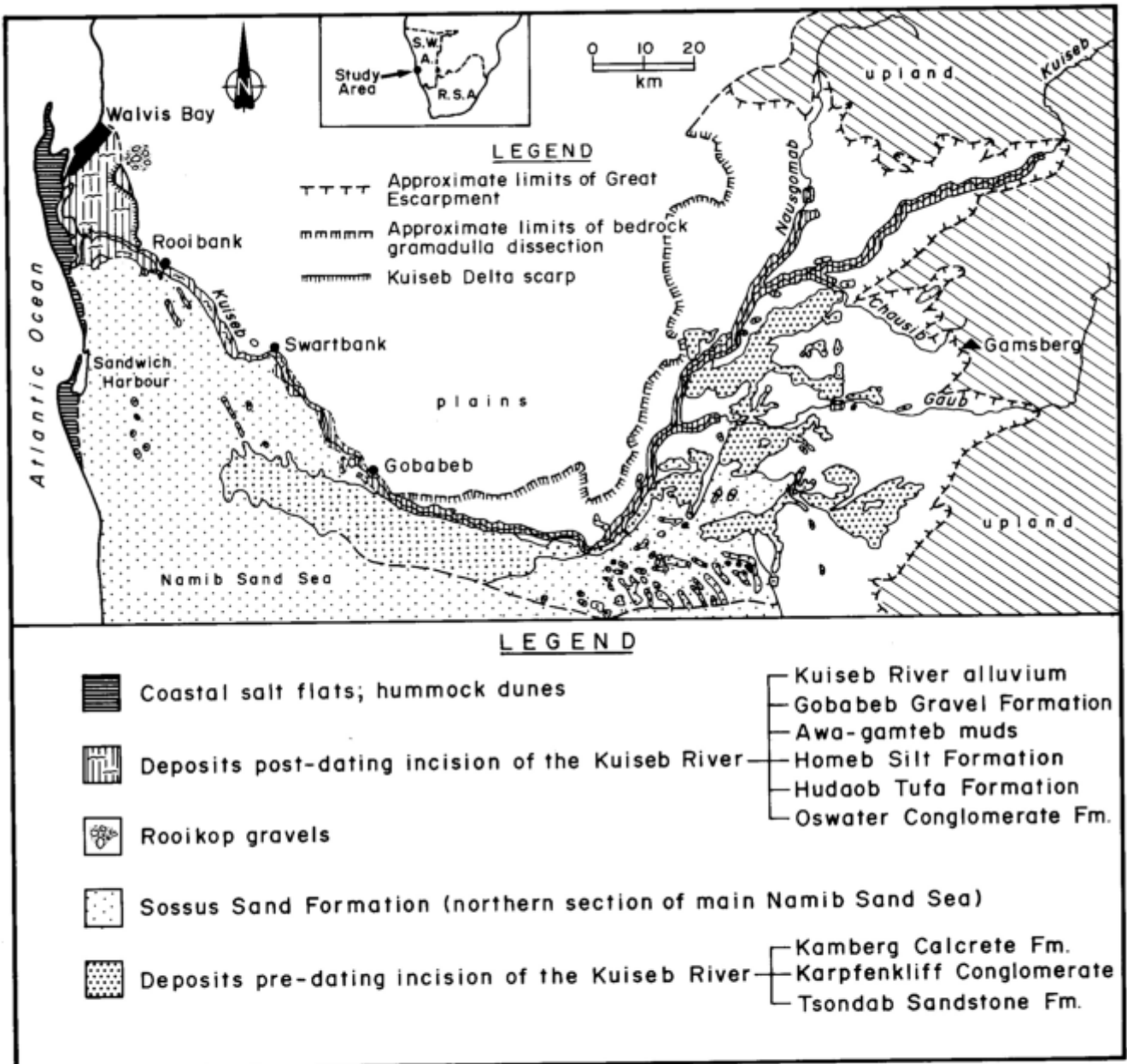


Figure 7: General distribution of the "pre-" and "post-incision" surficial deposits in the Kuseib Valley, west of the Escarpment.





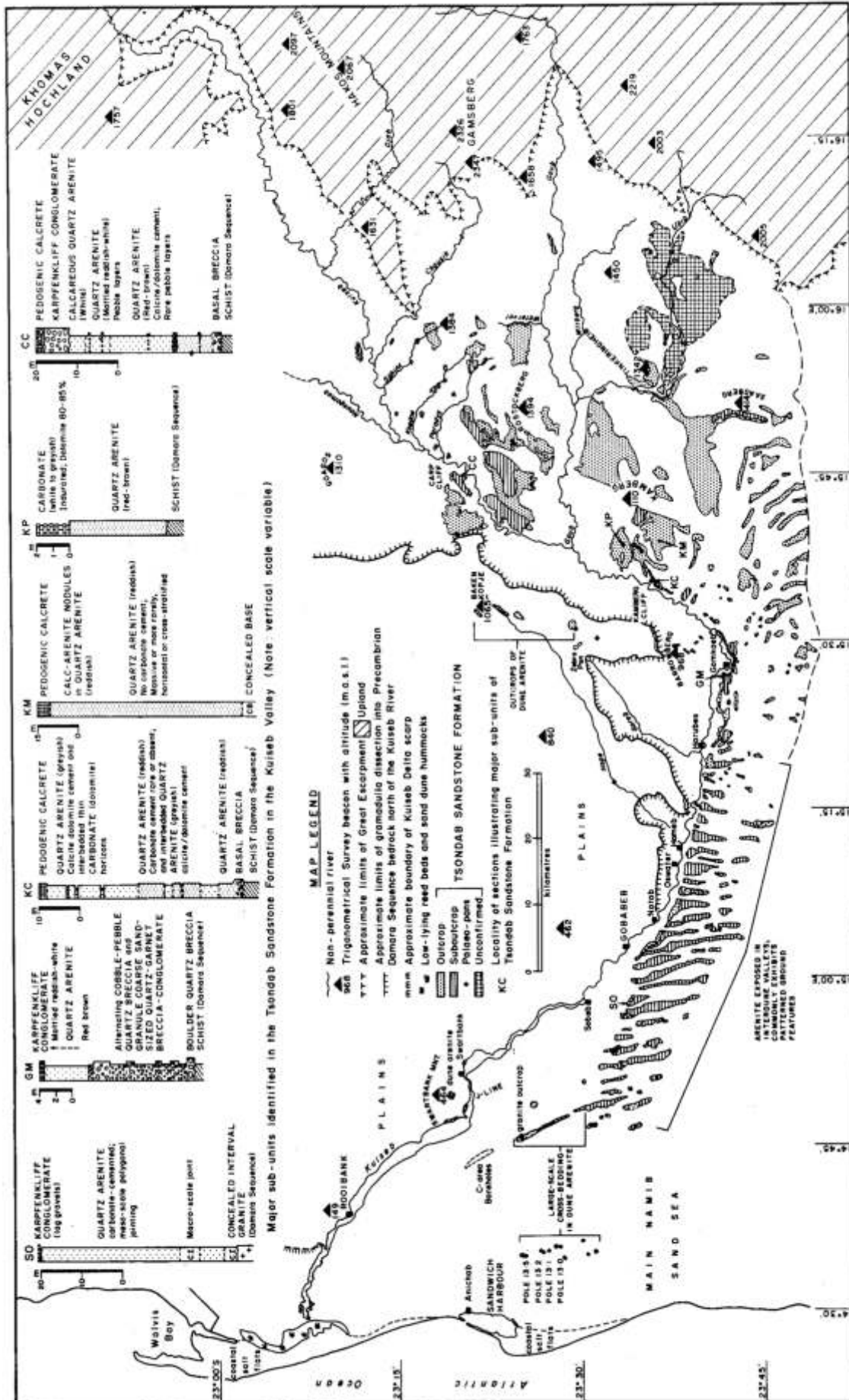


Figure 9: Distribution of the Tsondab Sandstone Formation in the Kuiseb Valley west of the Escarpment. Simplified reference sections of the six principal facies identified in the study area are shown.

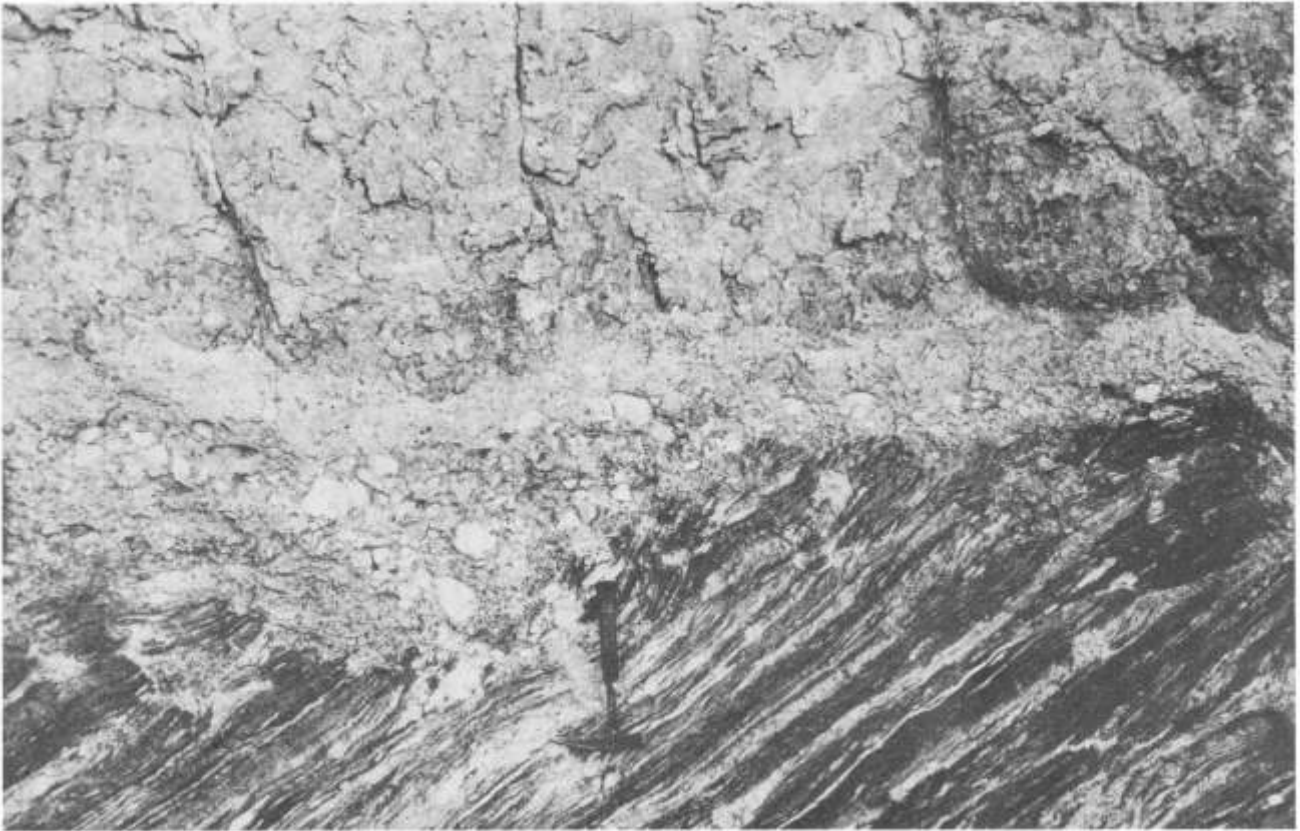


Figure 10: Gomkaeb Basal Breccia (Facies A) resting unconformably on Damaran schist. Gomkaeb corner, Kuiseb Canyon.

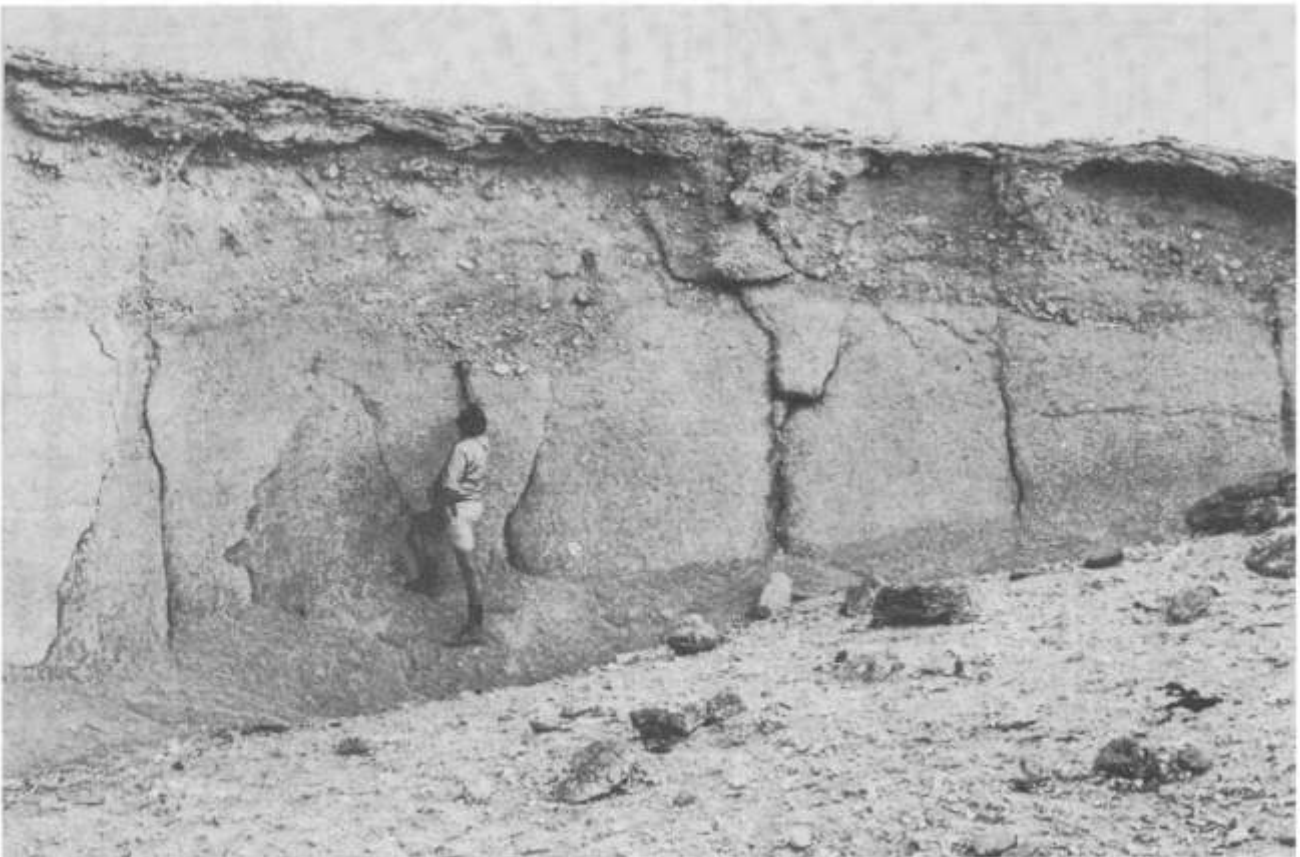


Figure 11: Cross-stratification within the breccia-conglomerate comprising Facies B deposits. Gomkaeb corner, Kuiseb Canyon.

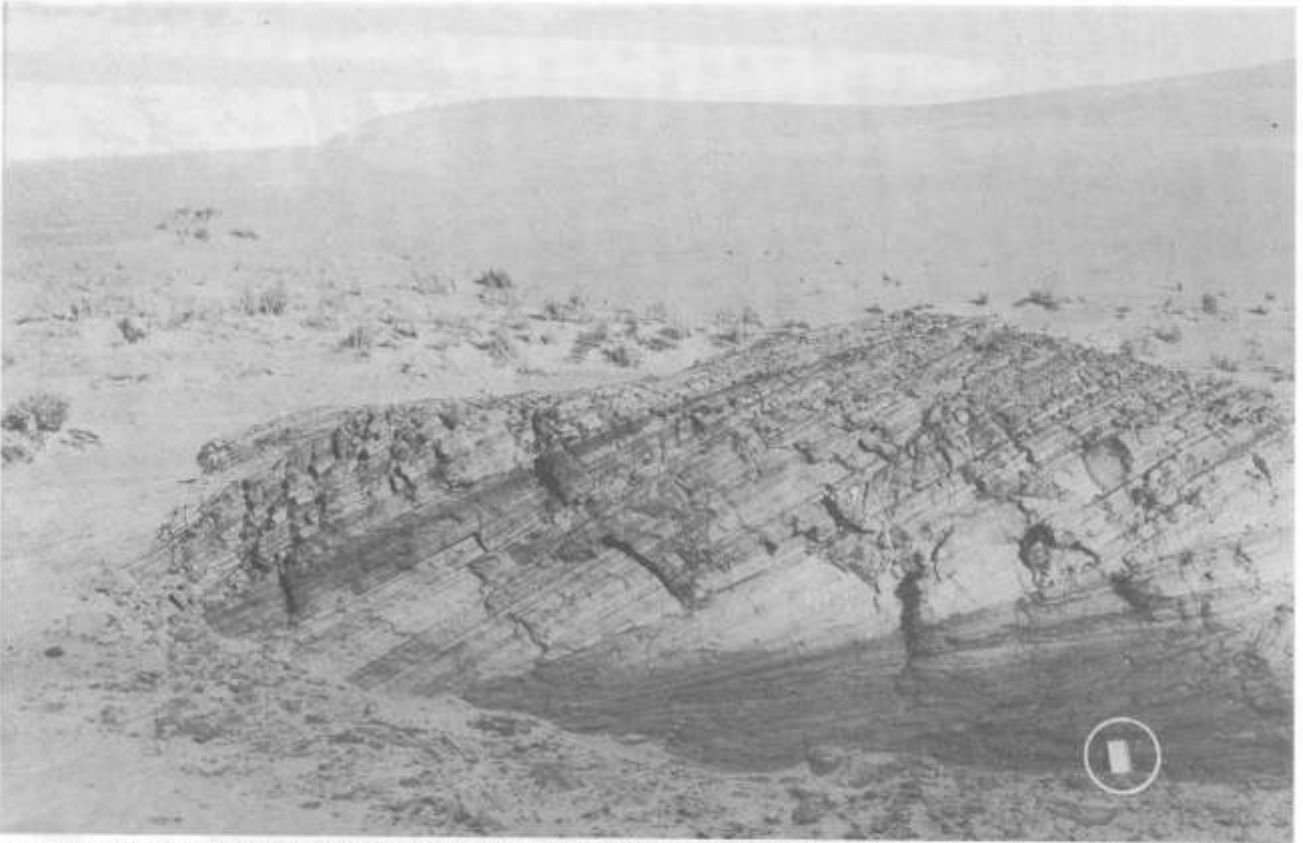


Figure 12(a): Large-scale cross-bedding, with a northward dip, in "typical" Tsondab Sandstone (Facies C) near J-line interdune valley. Notebook 15,5 cm high.

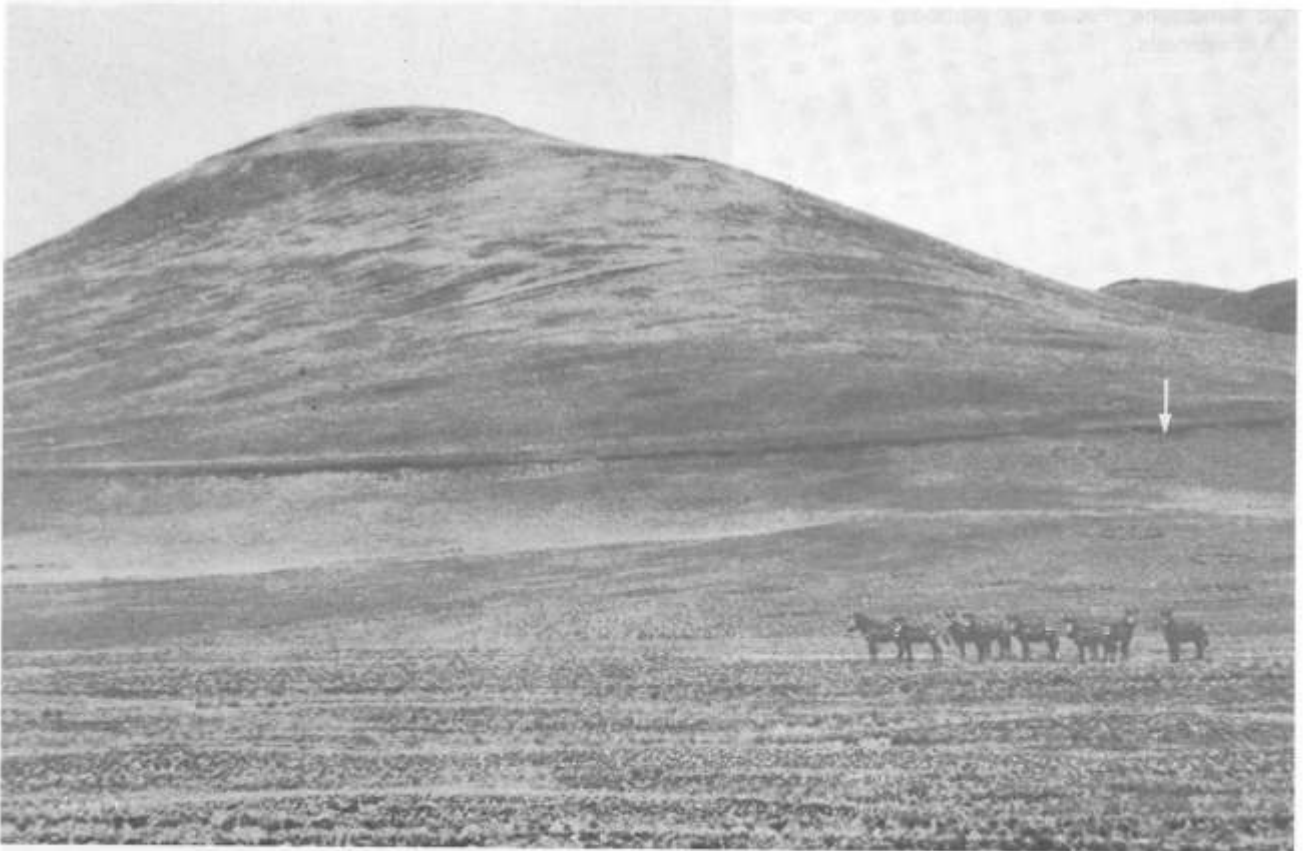


Figure 12(b): Large-scale cross-bedding and local unconformity (arrowed) in "typical" Tsondab Sandstone (Facies C) near the Kamberg.



Figure 13: Termite-like chamber in "typical" Tson-dab Sandstone (Facies C), Kamberg area. Scale 0,2 m intervals.

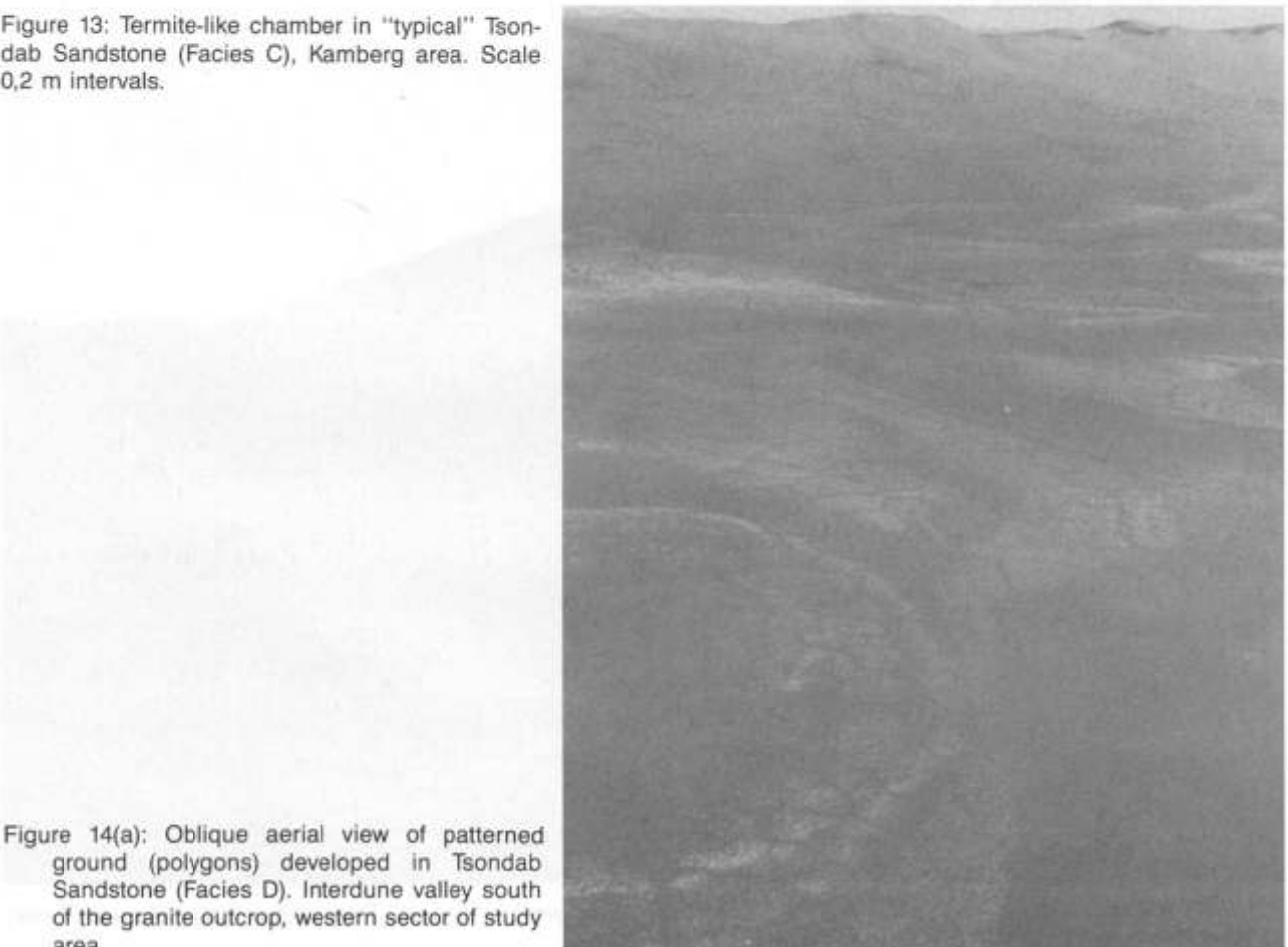


Figure 14(a): Oblique aerial view of patterned ground (polygons) developed in Tson-dab Sandstone (Facies D). Interdune valley south of the granite outcrop, western sector of study area.



Figure 14(b): Oblique aerial view of patterned ground (macro-factures) developed in Tsondab Sandstone (Facies D). Interdune valley south-south-west of granite outcrop, western sector of study area. Width of interdune c. 750 m.



Figure 15: Contact between cross-bedded arenite of Facies C and patterned ground arenite of Facies D. South-south-west of the granite outcrop, western sector of the study area.

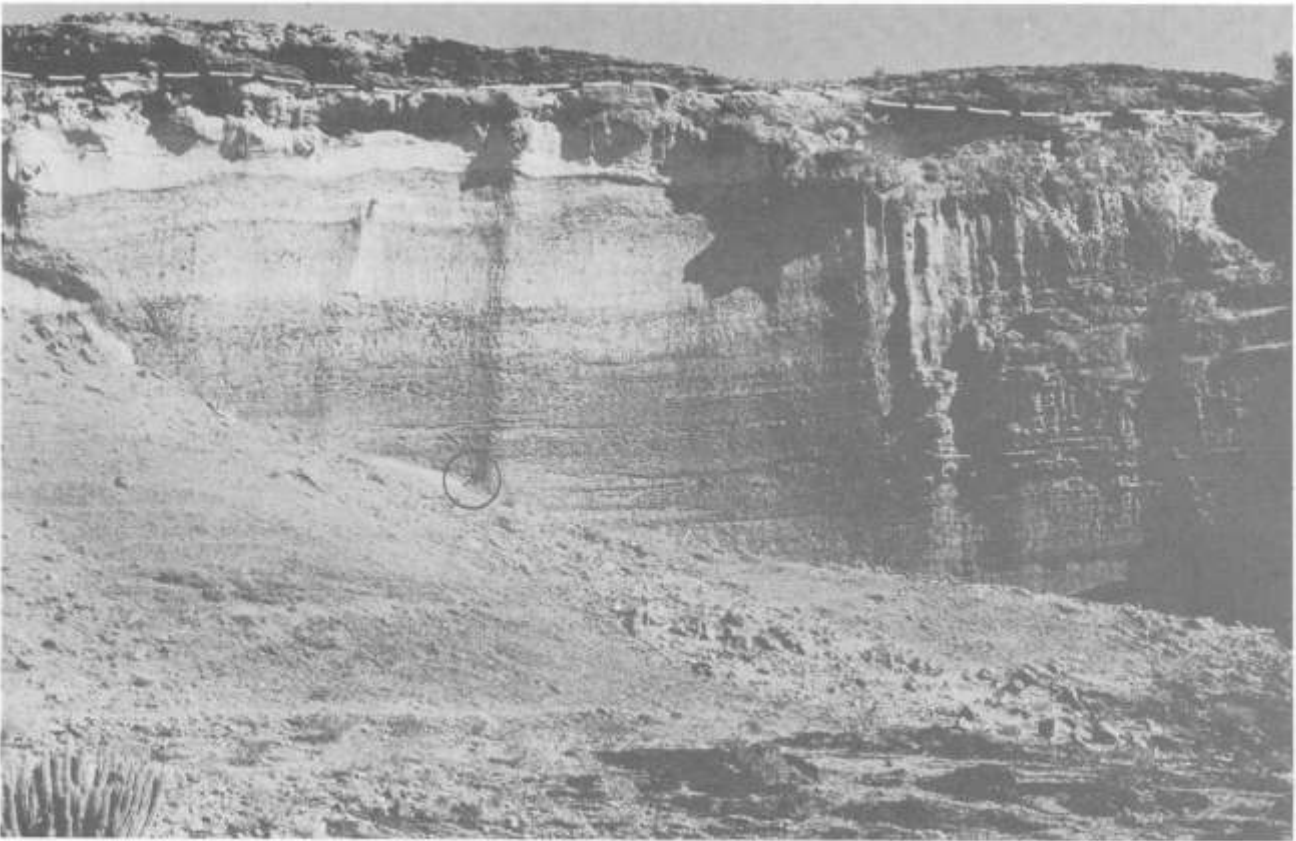


Figure 16: Proximal Facies E exposure at Carp Cliff. Note colour change in profile and poorly developed horizontal stratification. Upper contact to Karpfenkliff Conglomerate shown as (---). Cliff c. 45 m high, person (circled) for scale.



Figure 17: Distal Facies E exposure at Kamberg Cliff. Note large-scale stratification; Damaran bedrock exposed in wash. Cliff c. 50 m high, person (circled) for scale.

Figure 18: Pedotubules in Facies E arenite, Kamberg Cliff. Ranging rod 2 m.



Figure 19: Oblique aerial view of a Zebra Pan Carbonate deposit (Facies F) interbedded in Tson-dab Sandstone, Farm Oase/Namib-Naukluft Park boundary. This exposure is the "fossil lake" of Martin (1957, reprinted 1974, p. 70). Duricrusts of the Kamberg Calcrete Formation cap the landscape in the background. Game trails and fence for scale.







Figure 20: Casts of gypsum crystals in dolomite at the type locality of the Zebra Pan Carbonate (Facies F) near the Kamberg.

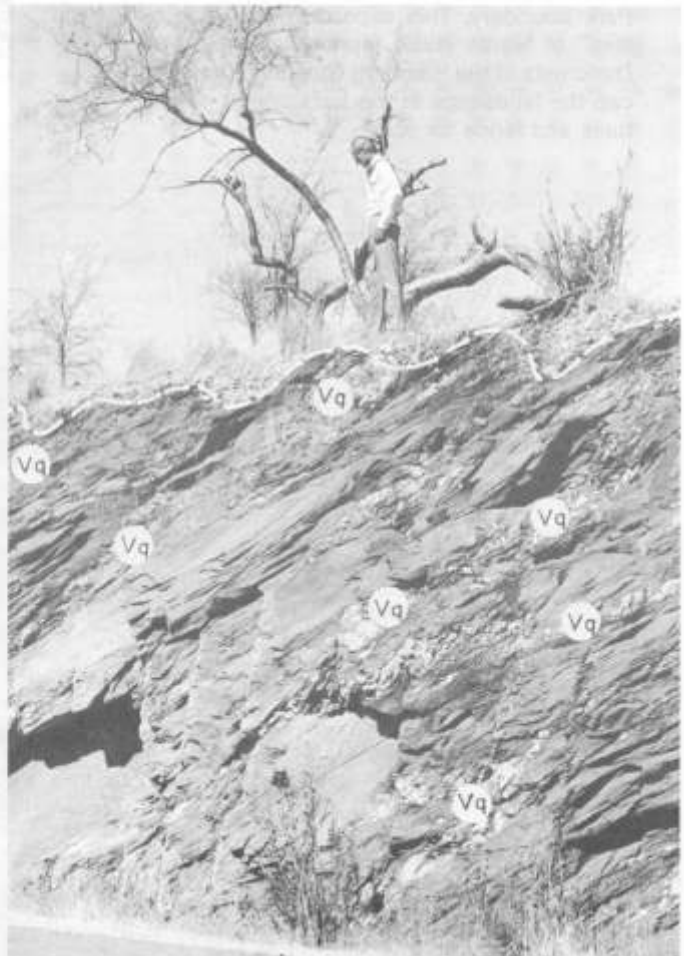


Figure 21: Skeletal lithosol, shown as (—), formed by a lag of vein quartz clasts derived from weathering of Damaran schist. Numerous quartz veins (Vq) cross-cut the schist. Daan Viljoen Game Reserve, Khomas Hochland (compare with Fig. 10).



Figure 22: Large-scale cross-stratification in a modern crescentic dune, western edge of the main Namib Sand Sea south of the Kuiseb Delta. Compare with Fig. 12.

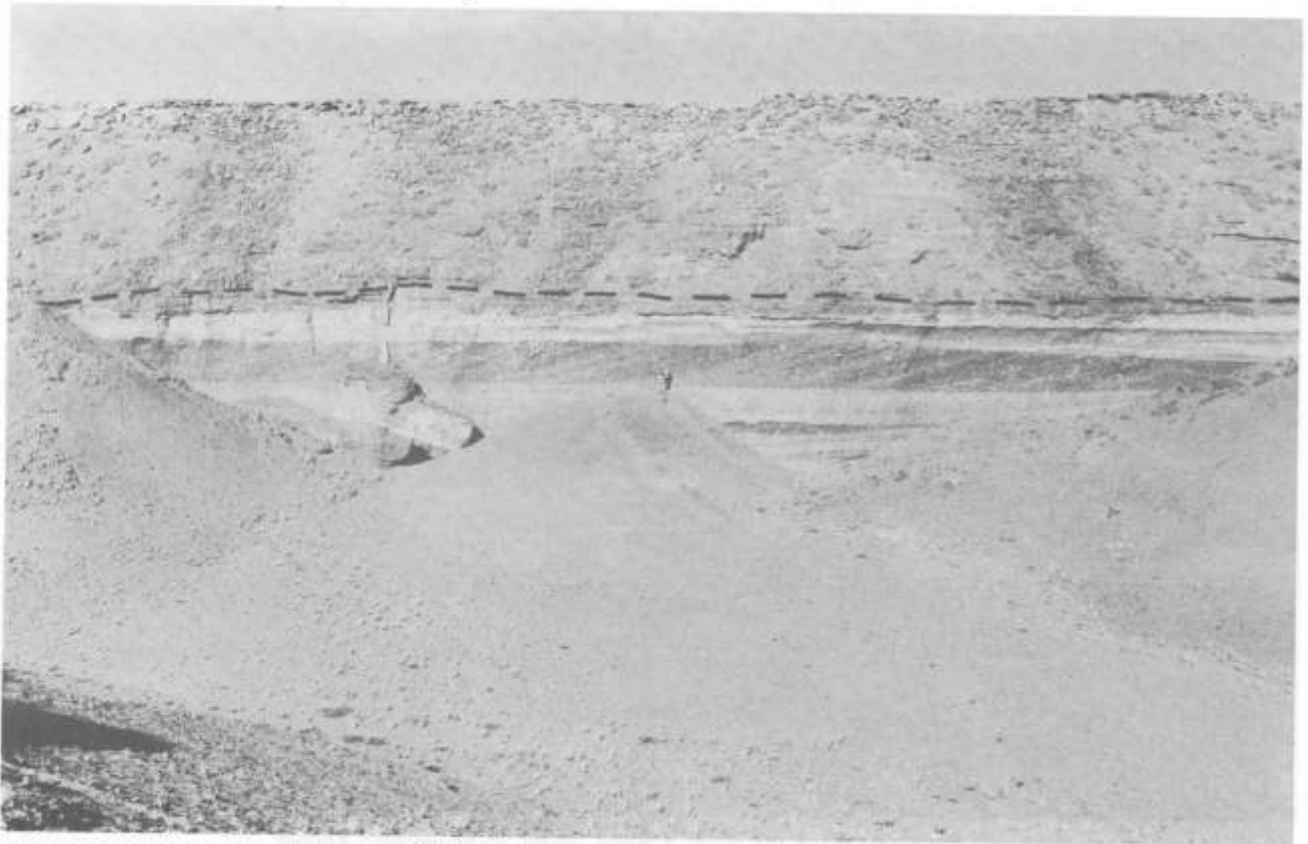


Figure 23: Laterally extensive, c. 3 m thick, bed of cross-stratified reddish arenite (Facies C) interbedded in carbonate-cemented Facies E deposits, Kamberg Cliff. Upper contact to Karpfenkliff Conglomerate shown as (---); person for scale.



(a): Buntfeldschuh escarpment, Sperrgebiet, Southern Namib. Aeolianite (Ba) overlies marine deposits (Bm) of probable Eocene age and is capped by a pedogenic calcrete (on skyline). Escarpment c. 90 m high.



(b): Red-brown arenites (arrowed) partly filling the lower Kunene Valley, south-western Angola.

Figure 24: Two examples of probable equivalents of the Tsondab Sandstone in the Namib Desert.



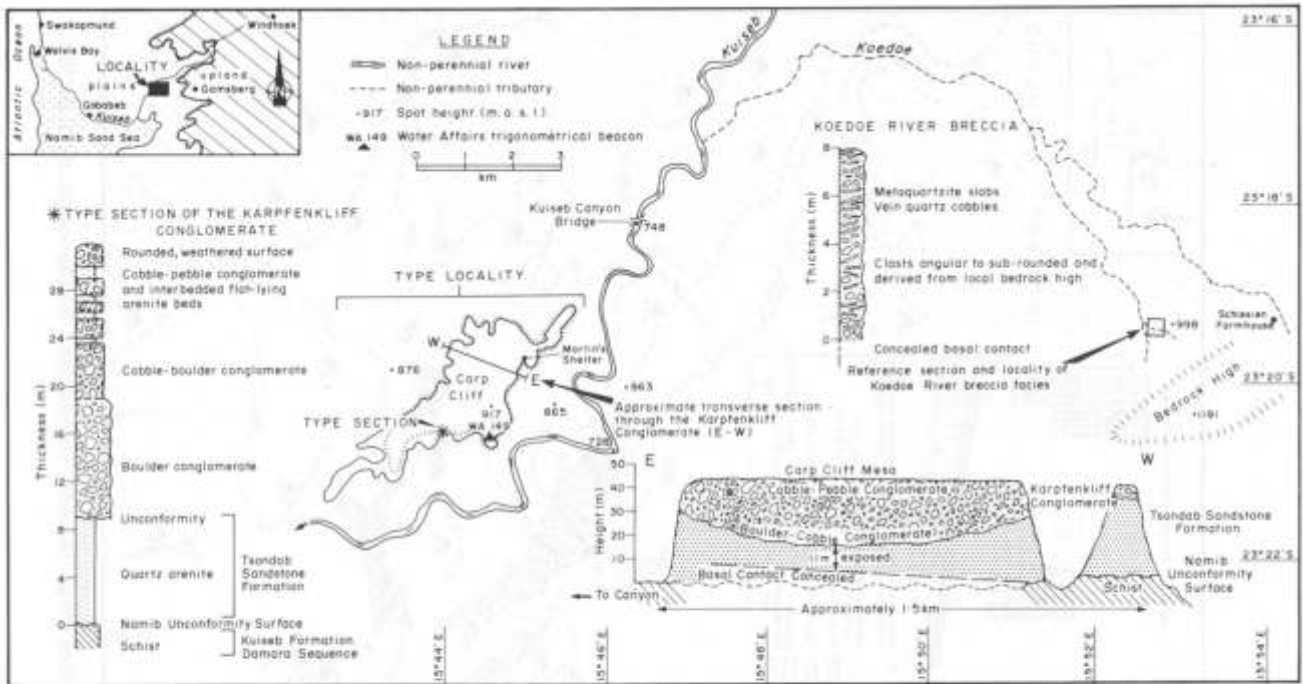


Figure 26: Type locality and section of the Karpfenkliff Conglomerate Formation in the Kuiseb Valley. Reference locality and section of the Koedoe River breccia facies is also shown.



Figure 27: Oblique aerial view south-westwards down the proto-Kuiseb from Carp Cliff. Tsondab Sandstone (Ts) rests directly on bevelled Damaran schist (Pc). The Karpfenkliff Conglomerate (Kk) overlies the Tsondab Sandstone and is capped by the Kamberg Calcrete (Kc). A terrace deposit of Oswater Conglomerate (Oc) is exposed within the Kuiseb Canyon.



(a): An c. 40m thick Karpfenkliff Conglomerate outcrop between the Sphinx and Chausib Rivers, proximal reach of the proto-Kuiseb Valley. Person for scale.



(b): Oblique aerial view north-westwards across the Gaub Valley at Rooiklip where Karpfenkliff Conglomerate (Kk), up to c. 40 m thick, rests directly on Late Recambrian bedrock (Pc).

Figure 28: Examples of thick exposures of Karpfenkliff Conglomerate near the base of the Escarpment.



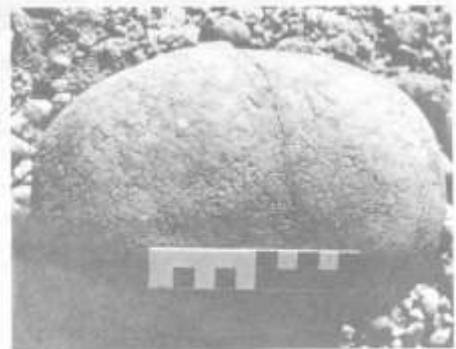
(a) Damara Sequence metaquartzite; Natasspruit. Ranging rod for scale.



(a)  
Small boulder. Scale 10 cm long.



(b) Vein quartz, Niedersachsen. Tree to right c. 1,5 m high.



(b)  
Cobble. Scale 10 cm long.

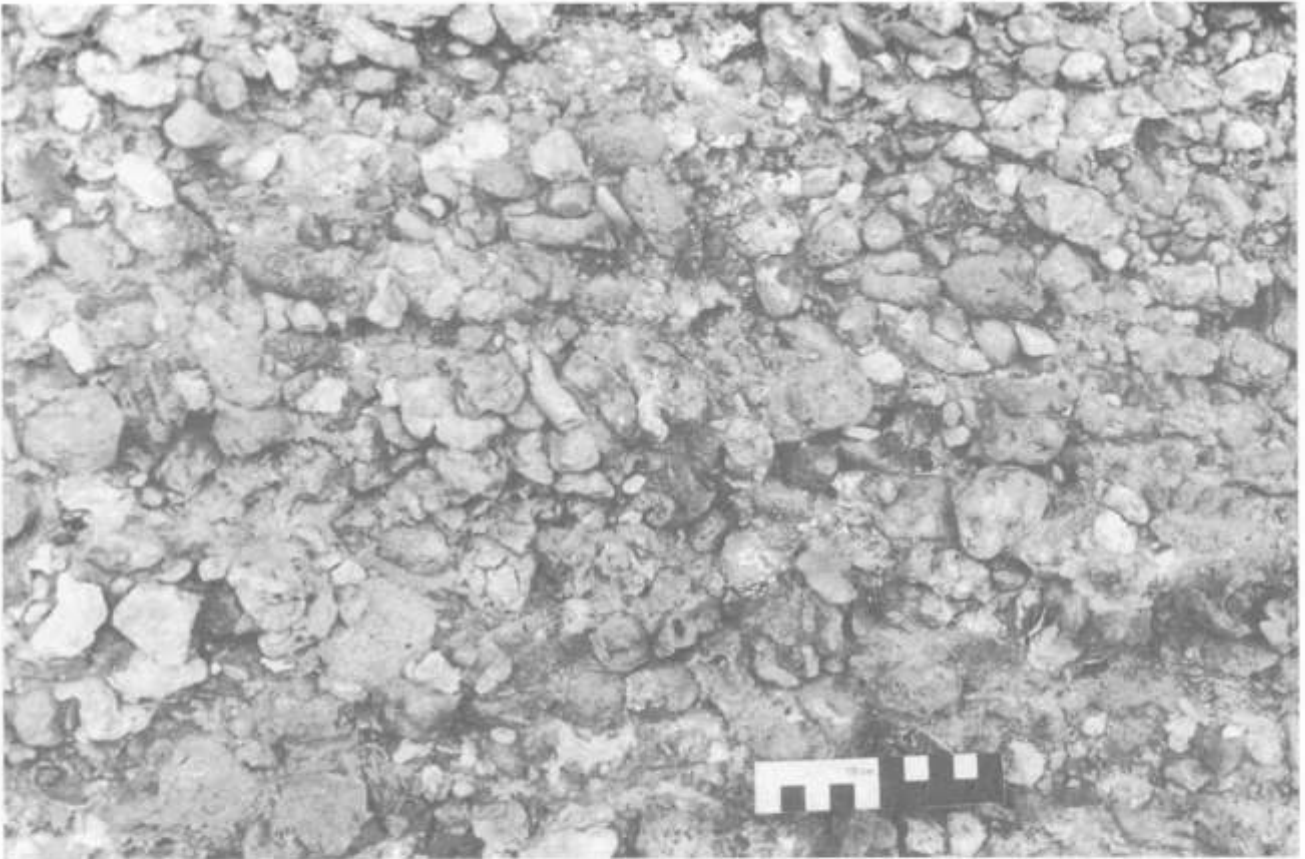


(c) Etjo quartzite, c. 25 m thick, capping the Gamsberg.

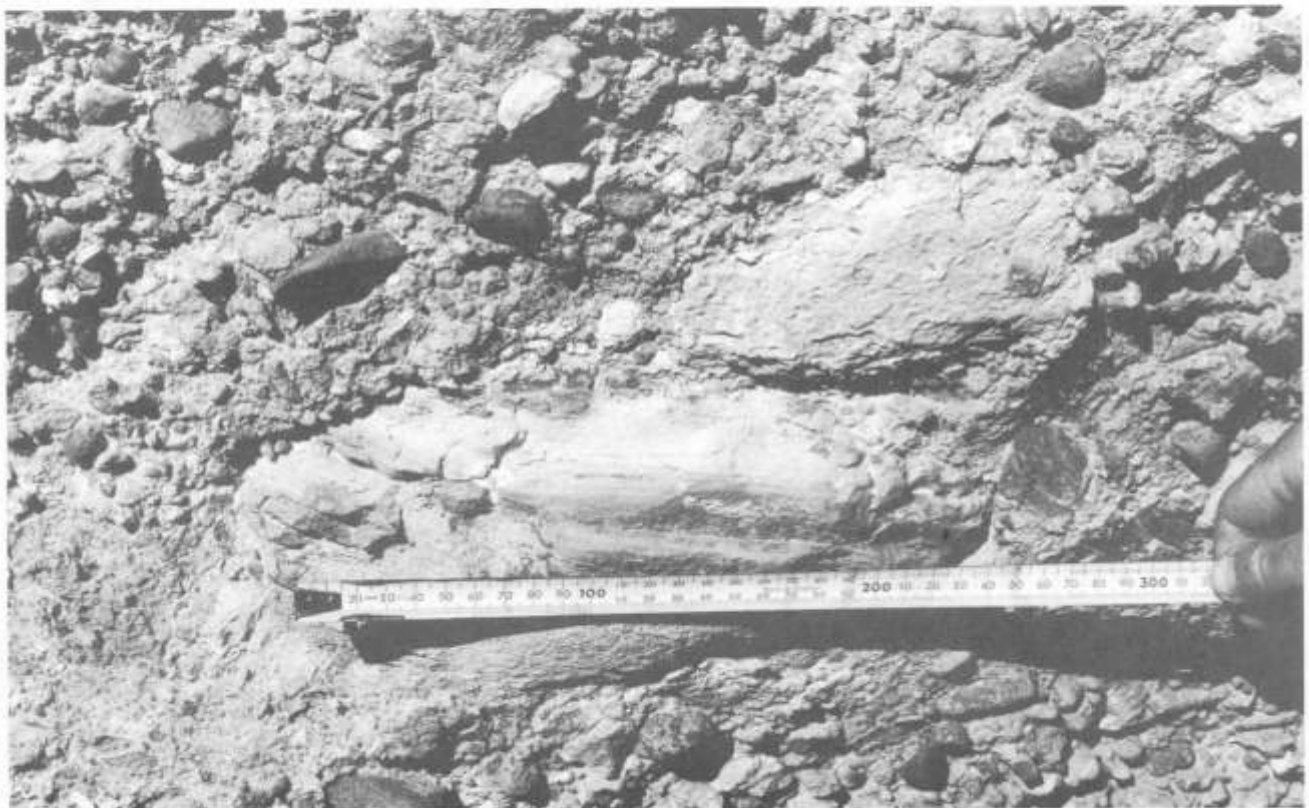


(c)  
Small boulder. Scale 10 cm long.

Figure 29: Exposures of the host rocks of the principal clast types in the Karpfenkliff Conglomerate.



(a): Water-worn pedotubules of reddish-brown, consolidated Tsondab Sandstone. Scale 10 cm long.



(b): Laminated Zebra Pan Carbonate clast above scale (in mm).

Figure 30: Clasts derived from the Tsondab Sandstone Formation in the Karpfenkliff Conglomerate at Kamberg Cliff.



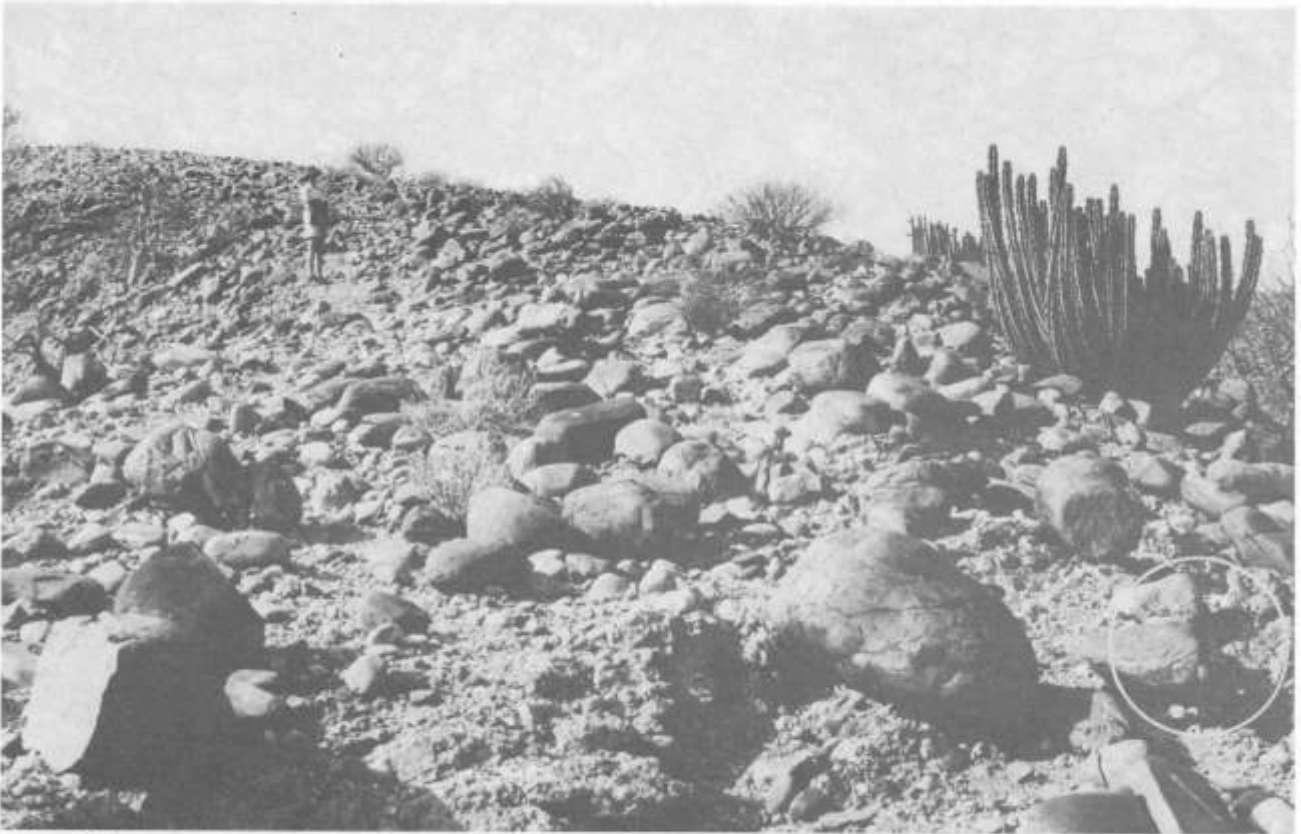
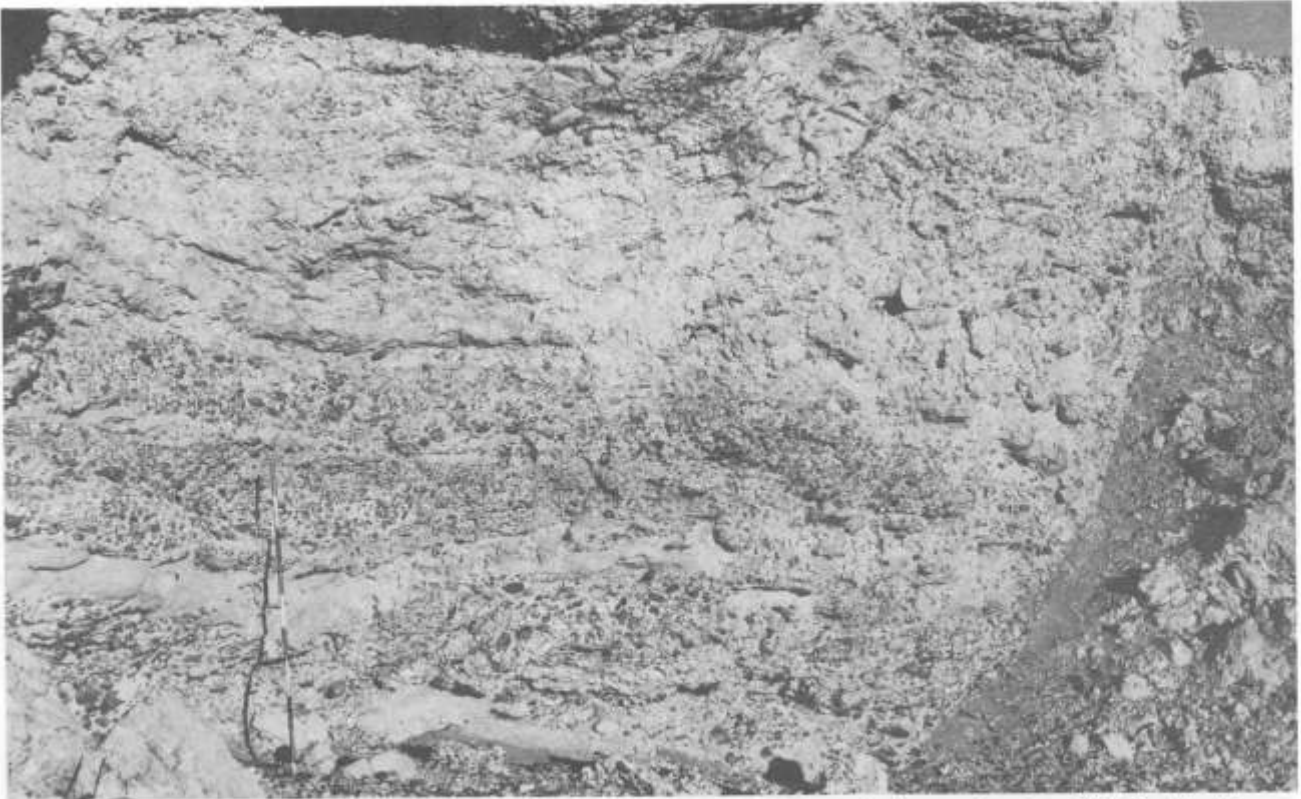
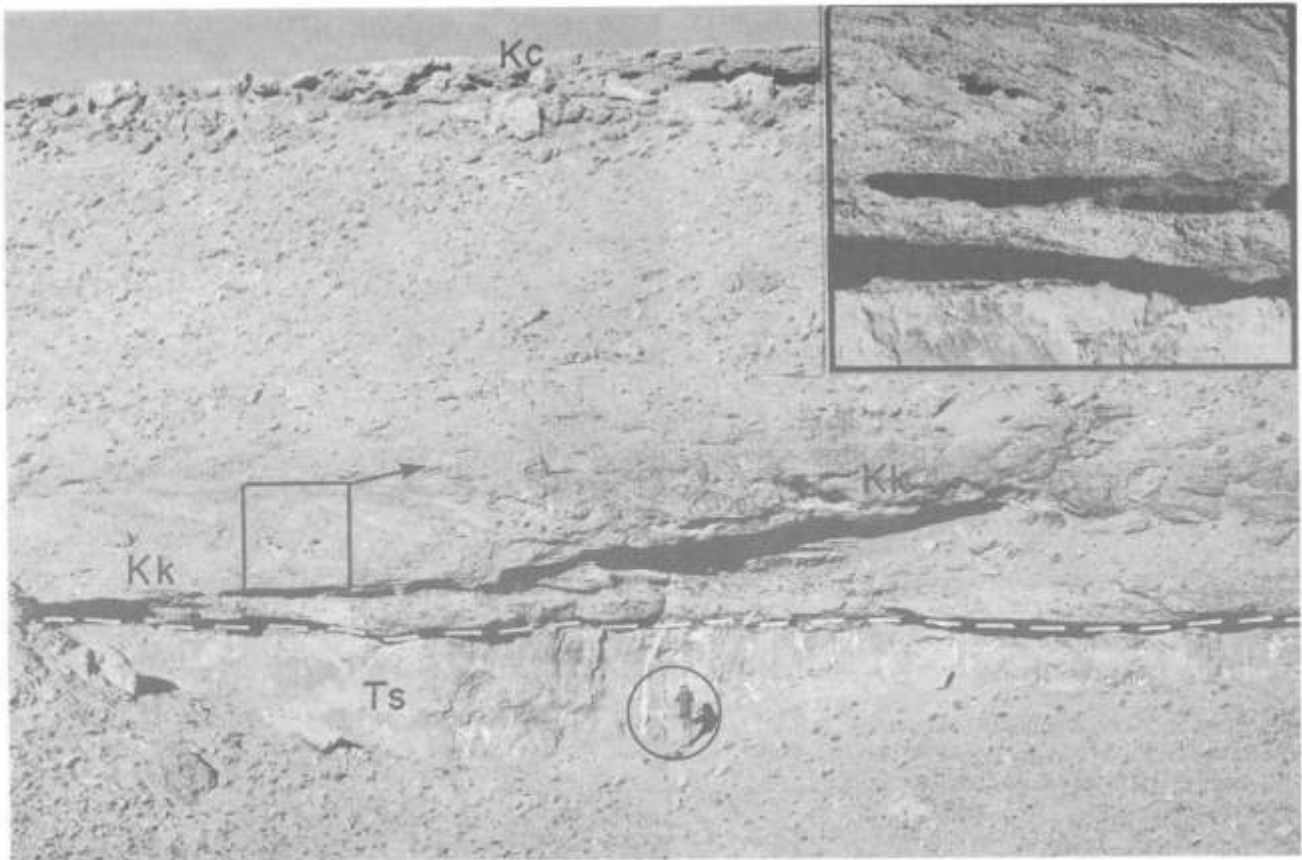


Figure 31: Large metaquartzite boulders weathered out of Karpfenkliff Conglomerate in the proximal reach. Sphinx River. Hammer (circled) in right foreground and person in background for scale.

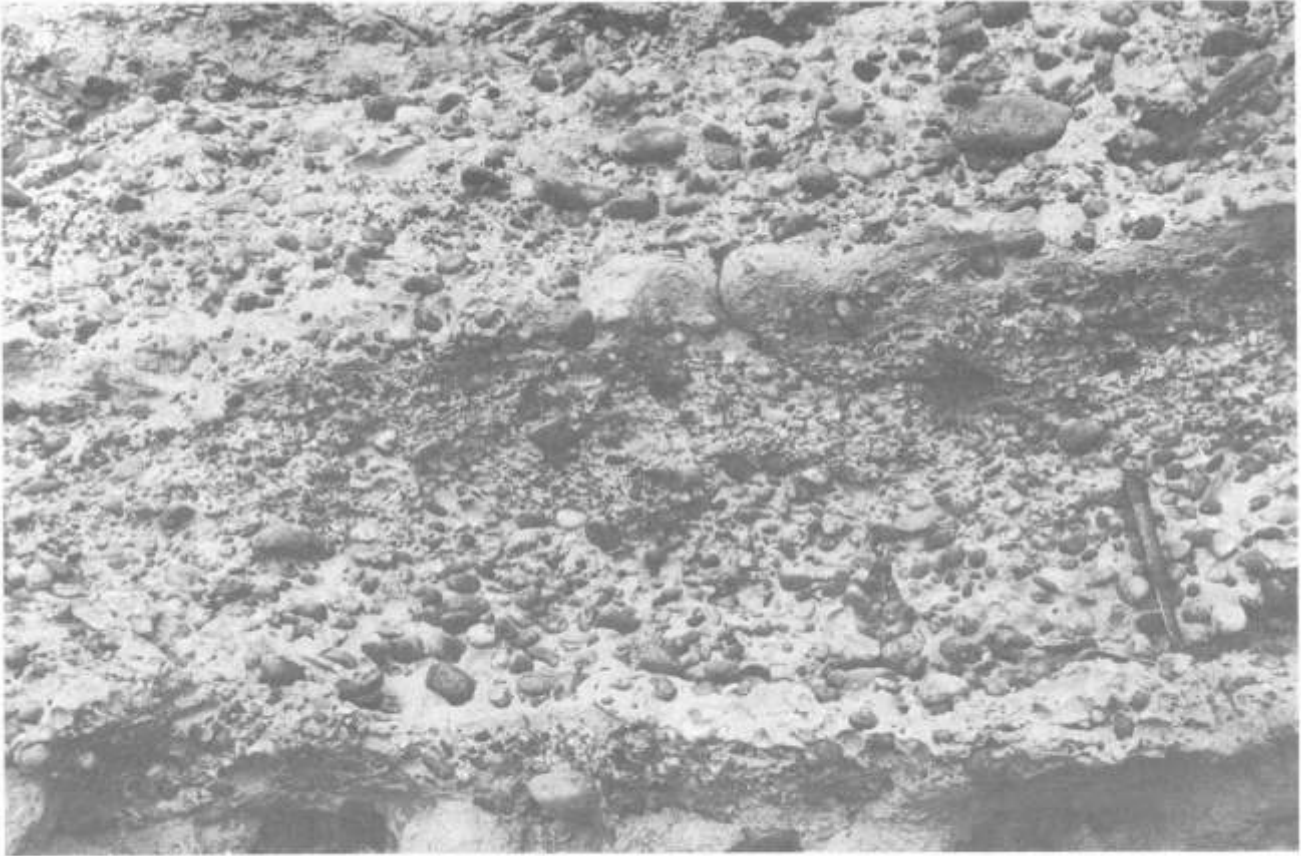


(a): Massive to crudely horizontally-stratified conglomerate and interbedded arenite layers, Kamberg Cliff. Gentle deformation is attributed to diagenetic calcification of the deposits. Ranging rod 2 m long.



(b): Cross-stratified conglomerate (Kk) above basal contact on Tsondab Sandstone (Ts). Inset shows closer view of cross-stratification and contact. Kamberg Calcrete (Kc) caps the Karpfenkliff Conglomerate. Person (circled) for scale.

Figure 32: Meso-scale stratification in Karpfenkliff Conglomerate at Kamberg Cliff.



(a): Horizontally-disposed, upward-fining, cobble/pebble/arenite unit. The matrix supported clasts illustrate the volume expansion associated with diagenetic calcification of Karpfenkliff gravels.



(b): Upward-fining, cobble/pebble/arenite unit in cross-bedded conglomerate exposure. This unit is part of a rhythmically-stacked sequence.

Figure 33: Small-scale, upward-fining units (< 1m thick) in Karpfenkliff Conglomerate at Kamberg Cliff.



Figure 34: Angular to sub-angular slabs of metaquartzite and poorly-rounded vein quartz clasts in a Koedoe River breccia exposure, Farm Schlesien. Ranging rod with 0,2 m intervals.



Figure 35: Thick sequence of Arries Drift Gravels exposed during diamond-mining operations. Bloeddrif, Lower Orange River, Southern Namib. Person (circled) for scale.

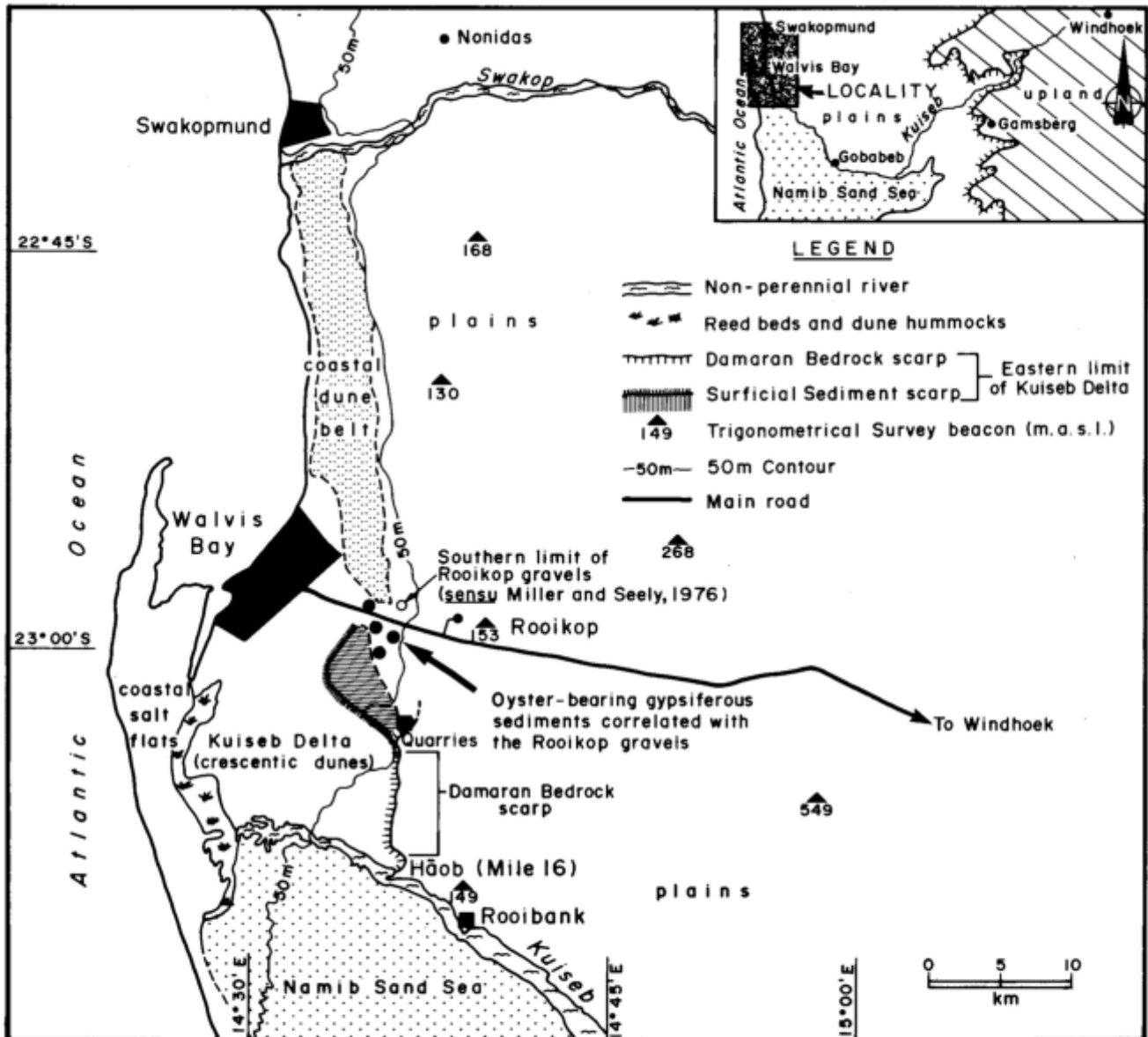


Figure 36: Location of the Rooikop gravel exposures in the study area. The southernmost position of the Rooikop gravels described by Miller and Seely (1976) is also shown.

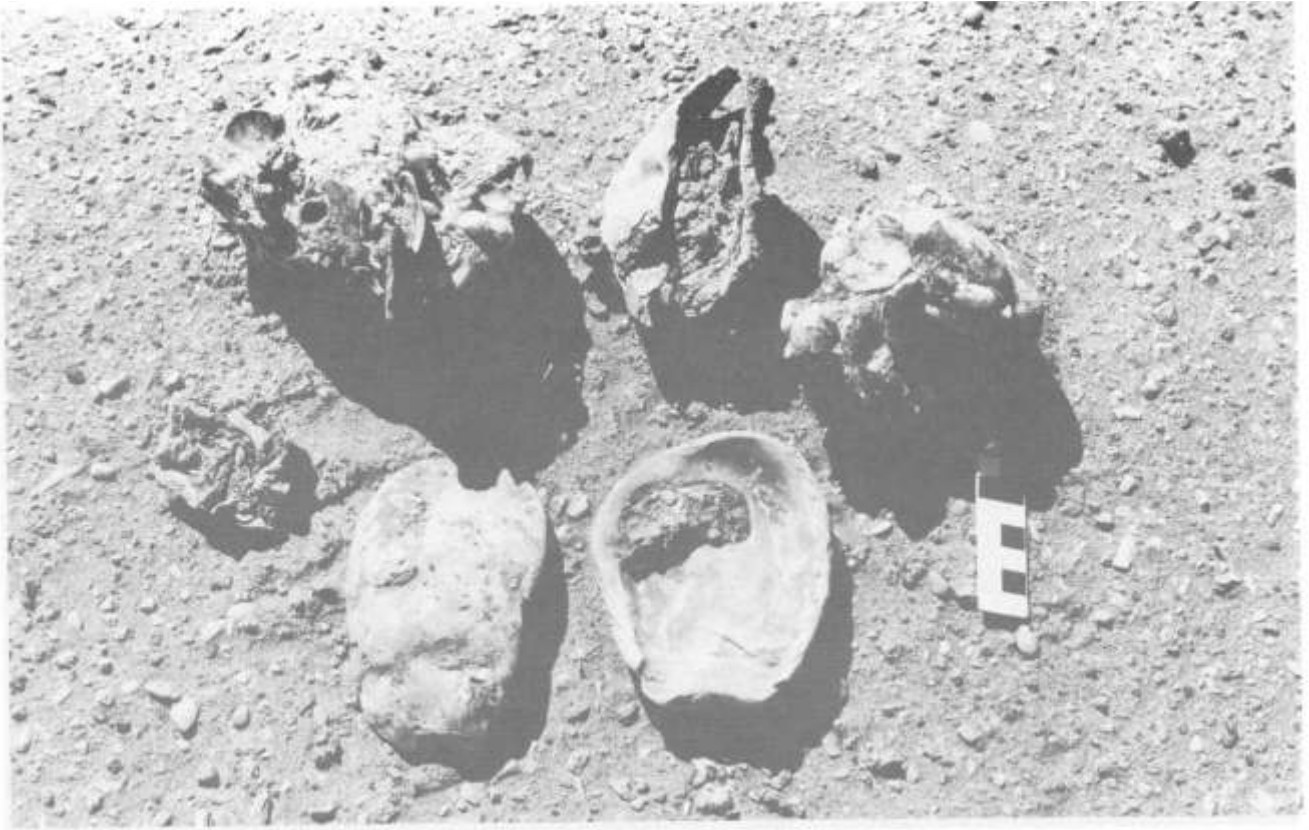


Figure 37: Robust oyster (*Striostrea margaritacea*) shells occur abundantly in the fossiliferous assemblage of the Rooikop gravels. Trench exposure north of Walvis Bay — Rooikop road. Scale in cm.

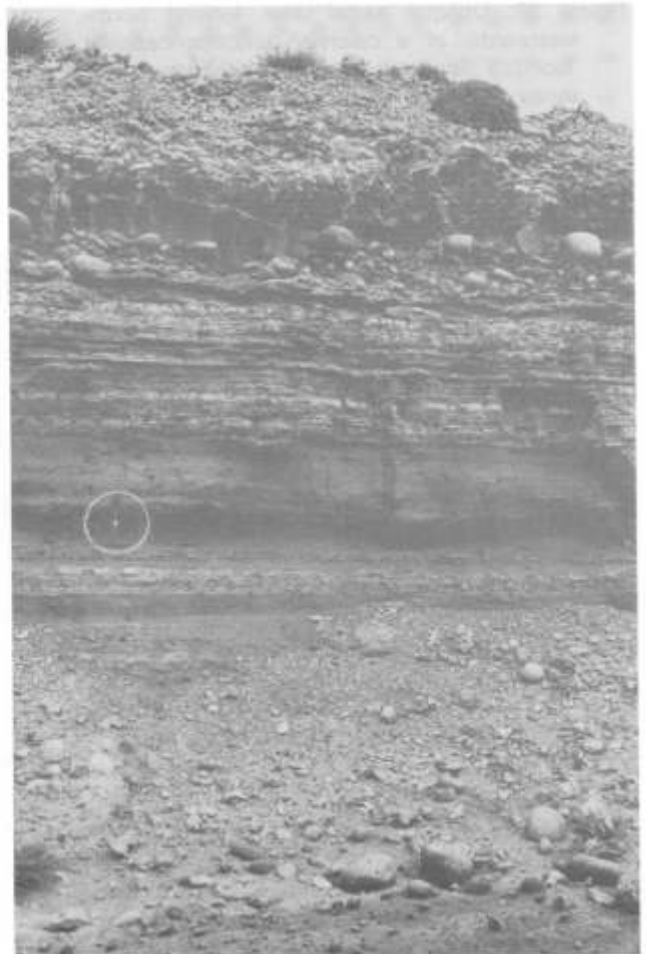


Figure 38: 'D beach' gravels resting on "false bedrock" of the Uubvley Clay channel, Sperrgebiet, Southern Namib.



Figure 39: Oblique aerial view, looking north-eastwards, of a calcrete duricrust capping Tsondab Sandstone near the Kamberg. The mesa is the type locality of the Kamberg Calcrete Formation (compare Figs. 19, 27).



Figure 41: Kamberg Calcrete profile in Tsondab Sandstone (Ts) at the type locality. Note the thick hardpan (Hd), honeycomb (Hc), and nodular (N) calcrete layers. Scale 1 m ranging rod. Compare with the type section in Fig. 40.

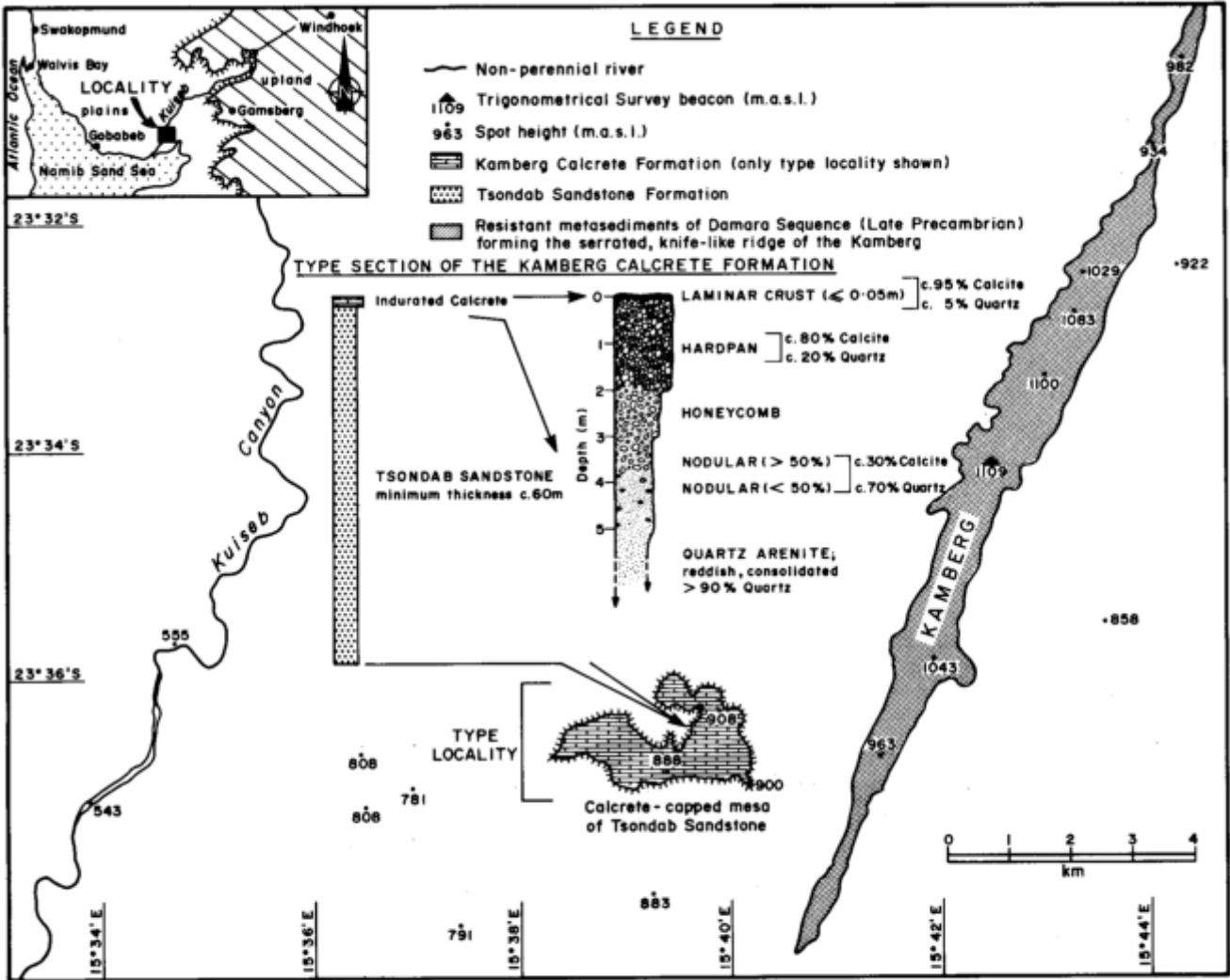


Figure 40: The type locality and section of the Kamberg Calcrete Formation in the Central Namib Desert (modified from Yaalon and Ward, 1982).



Figure 42: Small-scale, low-amplitude pseudo-anticlines (A) and -synclines developed in a thick Kamberg Calcrete (Kc) capping Tsondab Sandstone (Ts) near the type locality.

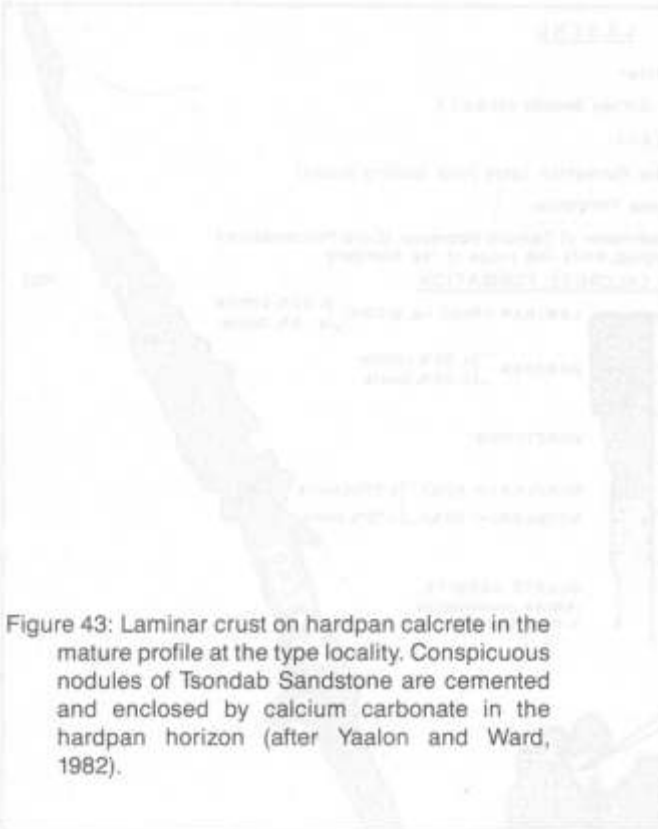


Figure 43: Laminar crust on hardpan calcrete in the mature profile at the type locality. Conspicuous nodules of Tsondab Sandstone are cemented and enclosed by calcium carbonate in the hardpan horizon (after Yaalon and Ward, 1982).





Figure 44: Kamberg Calcrete (Kc) capping a gentle slope (arrowed) between a higher, relatively flat-lying duricrust (1) and a lower level one (2). Berghof - Namib-Naukluft boundary. Rooiberg Mountain in the background (Pc). Compare duricrust levels in Fig. 19.

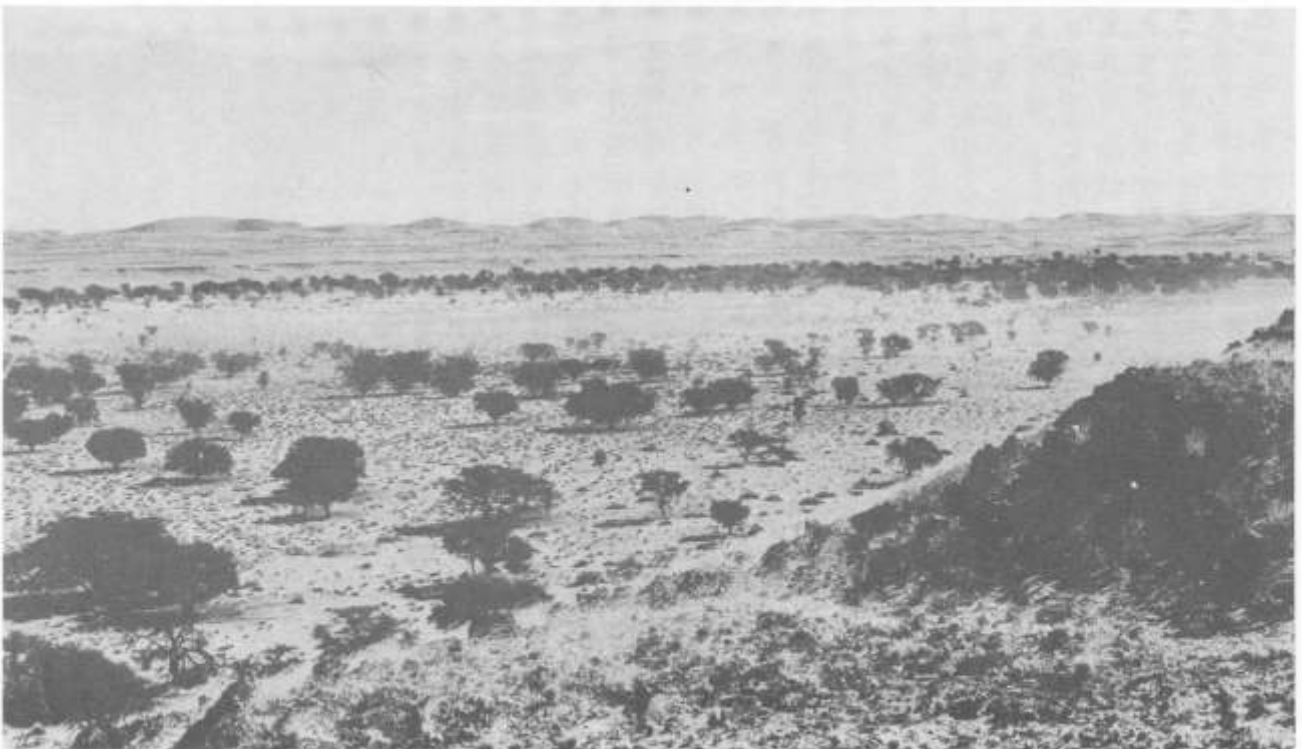


Figure 45: Calcareous dust blown out of fluviially-deposited silts and clays in the modern, ephemeral Tsondab River by a strong south-westerly wind, September 1979.

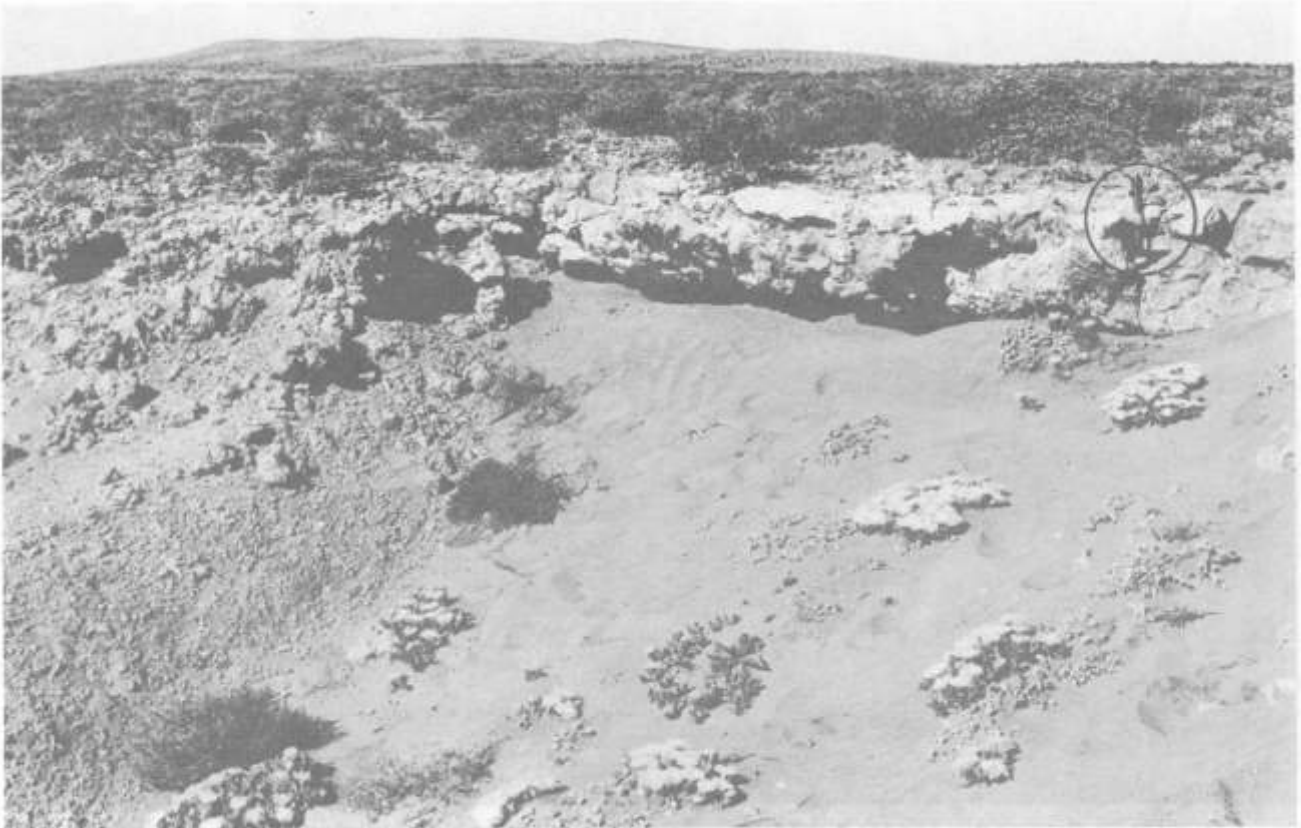


Figure 46: Calcrete duricrust of probable End Miocene age cropping out between Grillental and Swartkopp, Sperrgebiet, Southern Namib.



Figure 47: Terrace remnants of Oswater Conglomerate (Oc) within the Kuiseb canyon at Gomkaeb. The "pre-incision" Tertiary deposits cap the Namib Unconformity Surface on the canyon rim. Canyon depth 200 m. Canyon walls formed by Damaran schist (Pc).

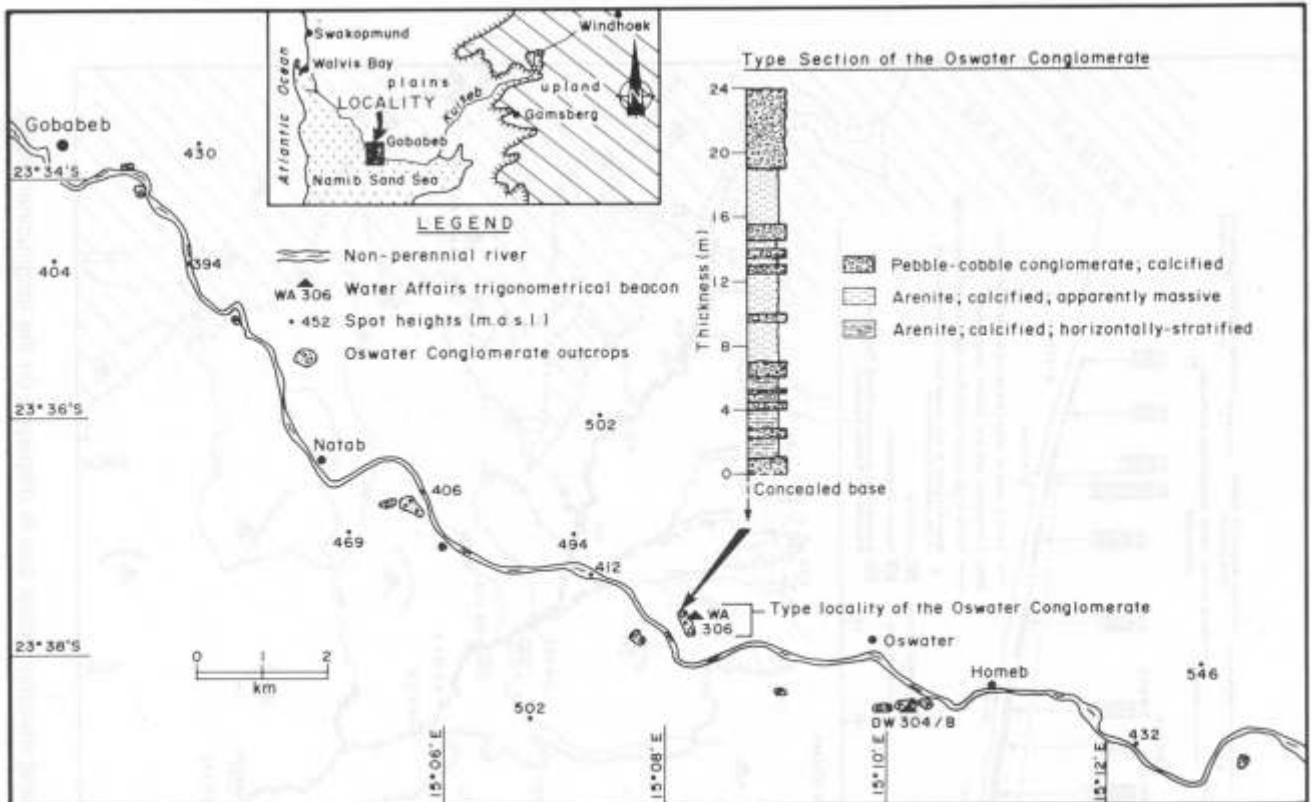


Figure 48: The type locality and section of the Oswater Conglomerate Formation.



Figure 50: Rounded clast of hardpan calcrete (arrowed) derived from the Kamberg Calcrete Formation and incorporated in the Oswater Conglomerate exposure at Hudaob. Scale 10 cm long.

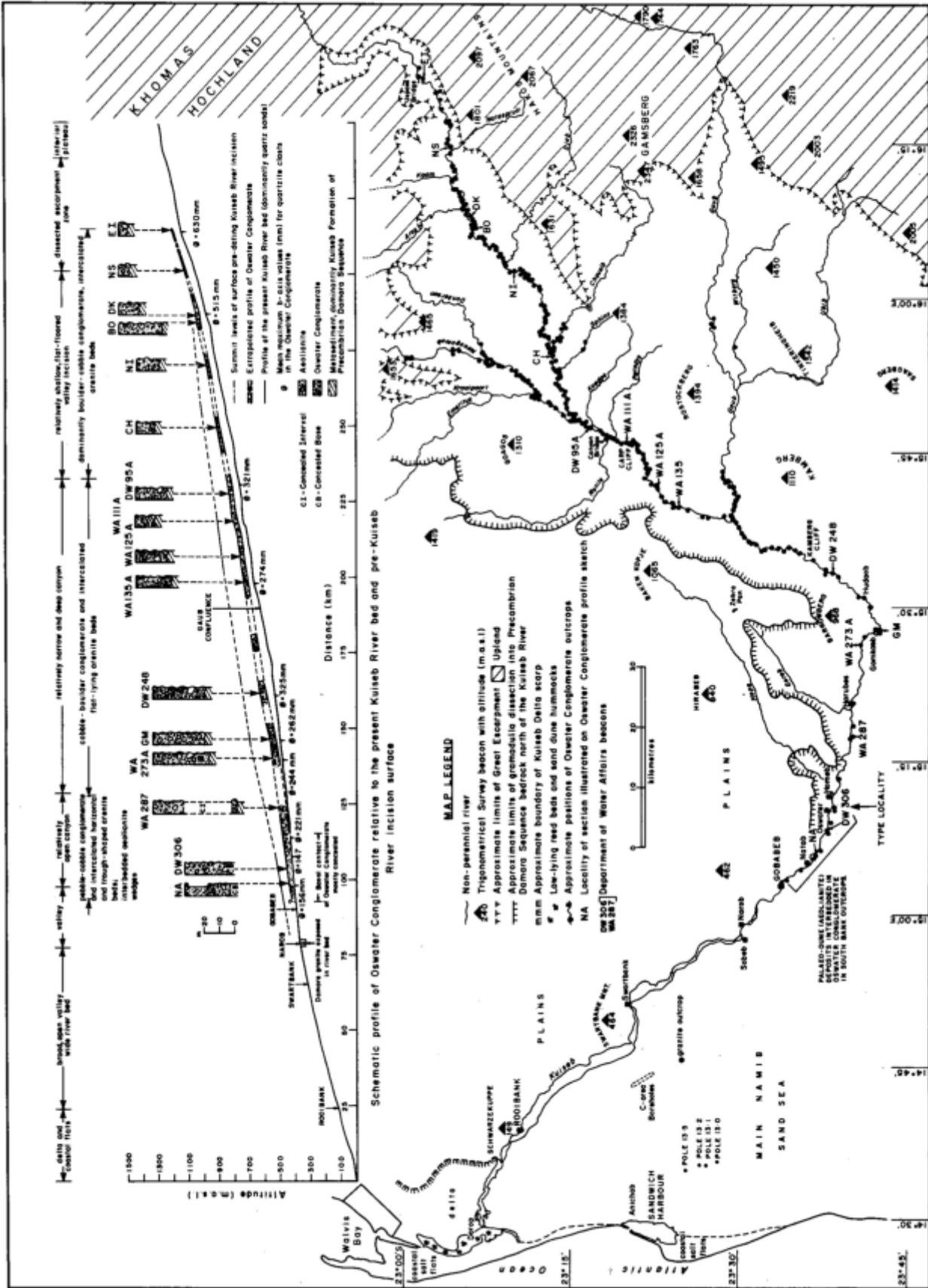


Figure 49: Distribution of the Oswater Conglomerate Formation. A summary of thickness and maximum clast size is displayed on the longitudinal profile.



Figure 51: View down the ancestral course of the incised Kuiseb River, DW 95 beacon area near Nausgomab-Kuiseb confluence. Oswater Conglomerate (Oc), with left (L), right (R) and basal (...) contacts visible, resting on bedrock (Pc). Oswater Conglomerate exposure in right foreground (Oc). Vehicle (circled) for scale in modern Kuiseb River bed.



Figure 52: Schist and vein quartz fragments derived locally from Damaran bedrock and incorporated into flat-lying beds of Oswater Conglomerate. The rudaceous units alternate with horizontally-disposed arenite layers and the basal contact onto bedrock is visible. WA 108 beacon vicinity near Kuiseb Canyon Bridge. Ranging rod 2 m long.



Figure 53: Steeply-dipping, large-scale stratification in a palaeo-dune wedge incorporated in an Oswater Conglomerate exposure near Natab.

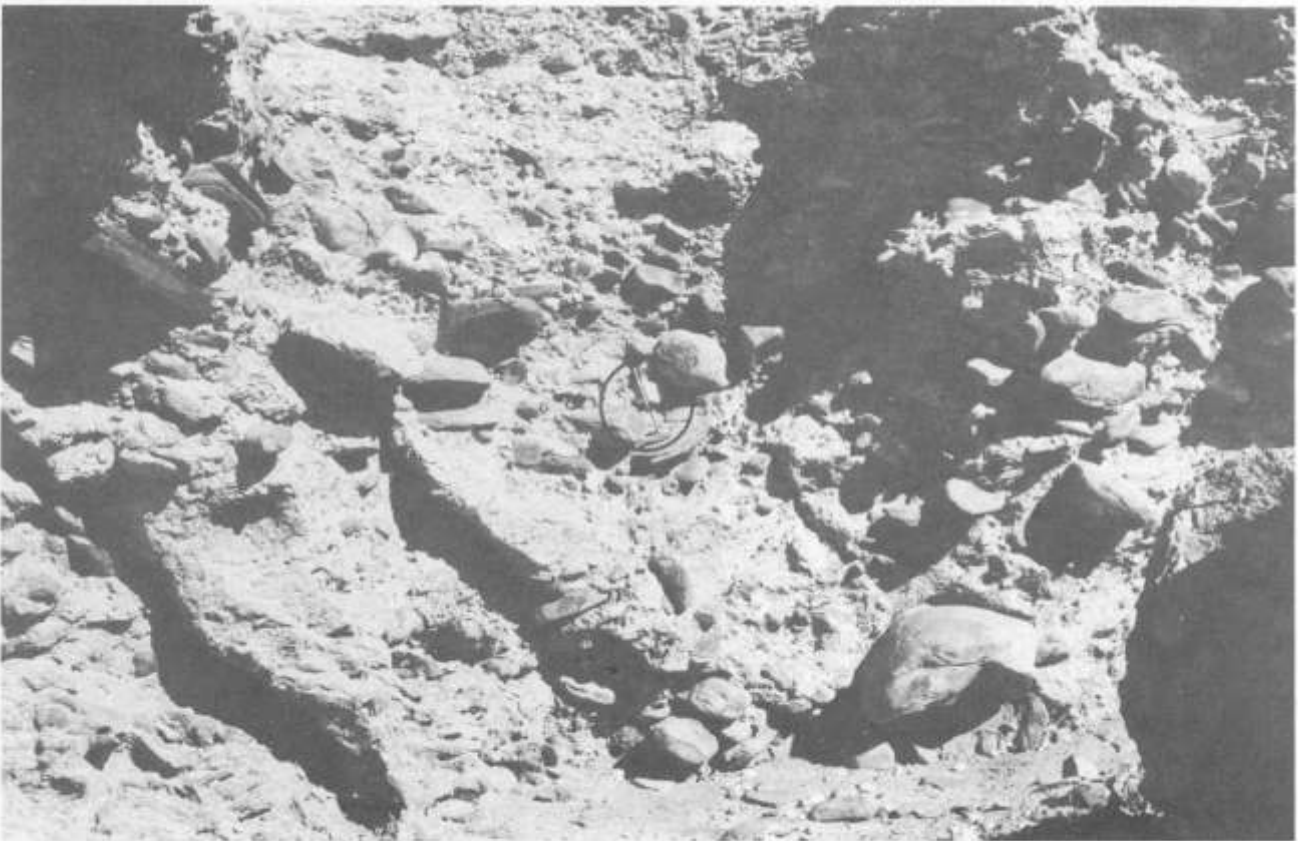


Figure 55: Boulder conglomerate of the Oswater Formation in the proximal reach, Aros - Kuiseb River confluence. Hammer for scale.

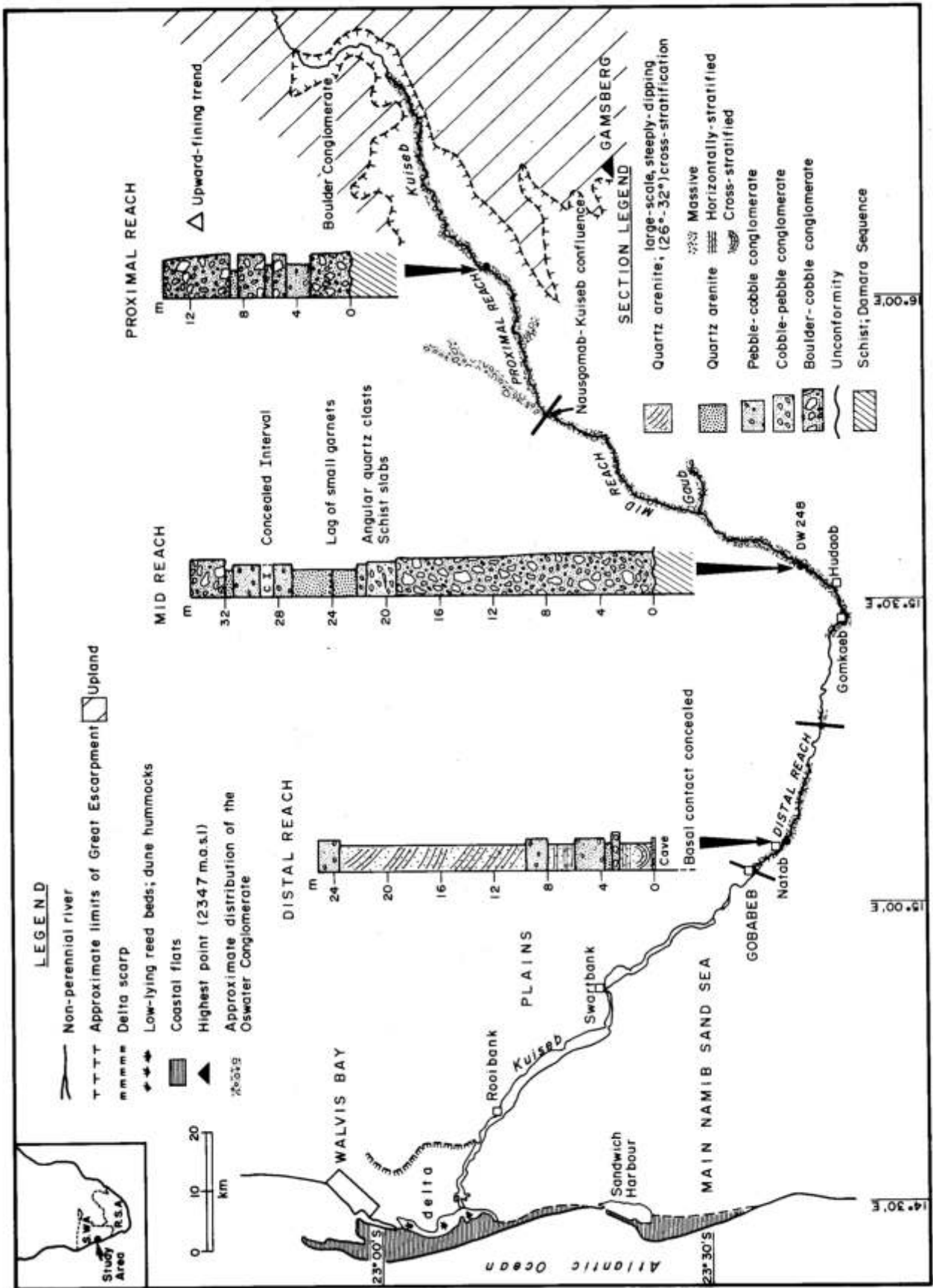


Figure 54: The three principal subdivisions recognised in the Oswater Conglomerate Formation within the Kuiseb Valley. Reference sections for these zones, notably the proximal, mid and distal reaches, are also shown.





Figure 56: Well cemented gravels in a mid reach Oswater Conglomerate exposure. Predominantly resistant quartzite and vein quartz clasts that are both clast- and matrix-supported. Flat-lying arenaceous interbed (c. 0,5 m thick) is a prominent layer (arrowed) in the conglomerate. WA 105 beacon area, c. 1 km downstream from Kuiseb Canyon Bridge.



Figure 57: Wedges of cobble-pebble conglomerate interdigitating with lenses of arenite in a distal Oswater exposure near Natab. Ranging rod intervals 0,2 m.



Figure 58: Low-angle, inclined stratification (arrowed) in a distal Oswater exposure near Natab.



Figure 59: Large channel-like lens of arenite cross-cutting conglomerate beds in a distal Oswater outcrop near Natab.



Figure 60: Complex channel-fill stratification in arenite and pebbly arenite units in a distal Oswater exposure near Natab. These units may be partly deformed by calcification of the sandy deposits. Scale 2 m ranging rod.



Figure 61: Complex linear dune fronting onto the Lower Kuiseb River at Natab East, c. 14 km upstream from Gobabeb.



(a): Fluvial bedforms, chiefly mud-draped ripples, exposed on the Kuiseb River bed one day after the termination of the March 1981 flood. Gorob- Kuiseb confluence. Scale 1 m ranging rod (circled).



(b): Same locality, June 1981. Re-shaping of Kuiseb River bed by aeolian processes. Partial removal of muddy silts by aeolian action following desiccation. Note aeolian ripples on sandy river bed.

Figure 62: The destruction of fluvial bedforms in the modern Kuiseb River after c. 3 months of subaerial exposure, desiccation and aeolian processes. Note the redistribution of river sands by winds which has resulted in an infilling of the interstitial spaces between clasts in the left foreground (arrowed). Bedrock = Pc.



Figure 63: Wind deflation in the modern Kuseb River bed producing clusters of clasts alternation with sandy patches, similar to the pattern observed on the surface of arenite beds in mid reach Oswater exposures (inset, scale in mm). The river-derived sand hummocks trapped at the base of the riverline vegetation (background) testify to aeolian winnowing of the Kuseb bed. Schlesien weir, Kuseb canyon.

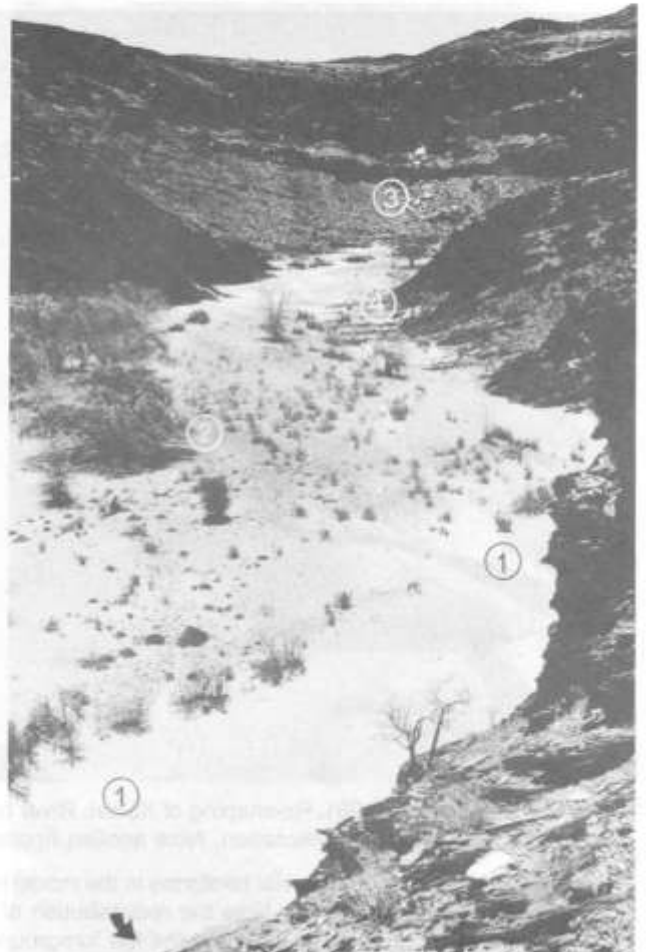


Figure 64: View upstream of the ephemeral Kuseb River, near the Canyon bridge, to illustrate modern analogues for the Oswater Conglomerate. Vehicle track (arrowed) for scale.

1. Flat-lying sandy river bed subjected to wind deflation processes.
2. Gravel bar, partially covered by river sands redistributed by wind.
3. Talus of locally-derived schist slabs.
4. Bedrock exposed in river bed and near left-bank contact.



Figure 65: Cemented boulder-cobble gravels forming a flat-lying terrace deposit on bedrock (Pc) in the Lower Ugab Valley, Skeleton Coast. View downstream; *Acacia albida* trees (10–12 m high) in modern Ugab River for scale.

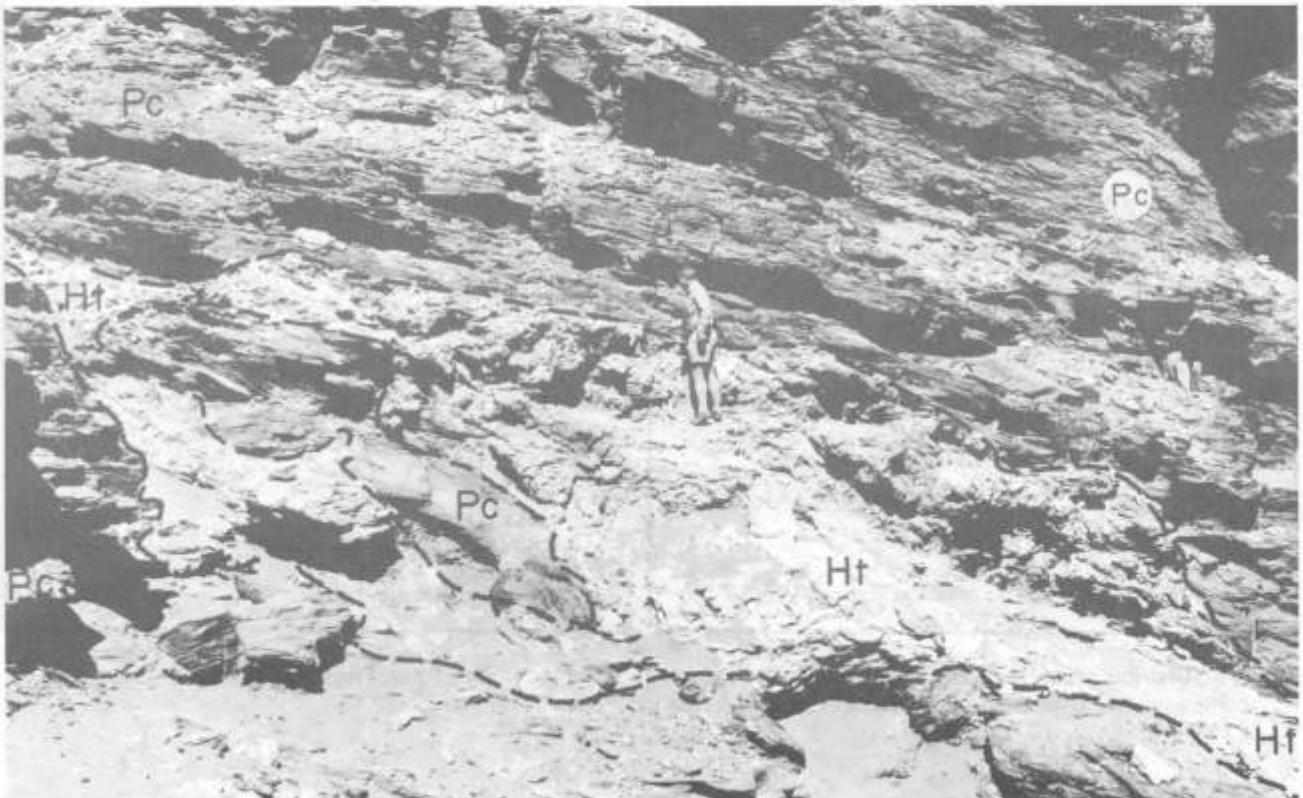


Figure 66: Pale-coloured tufa deposit (Ht) forming a thin, irregular carapace (outlined ---) on Damaran schist exposed in a tributary wash of the Kuiseb River. Type locality at Hudaob, Kuiseb Canyon.

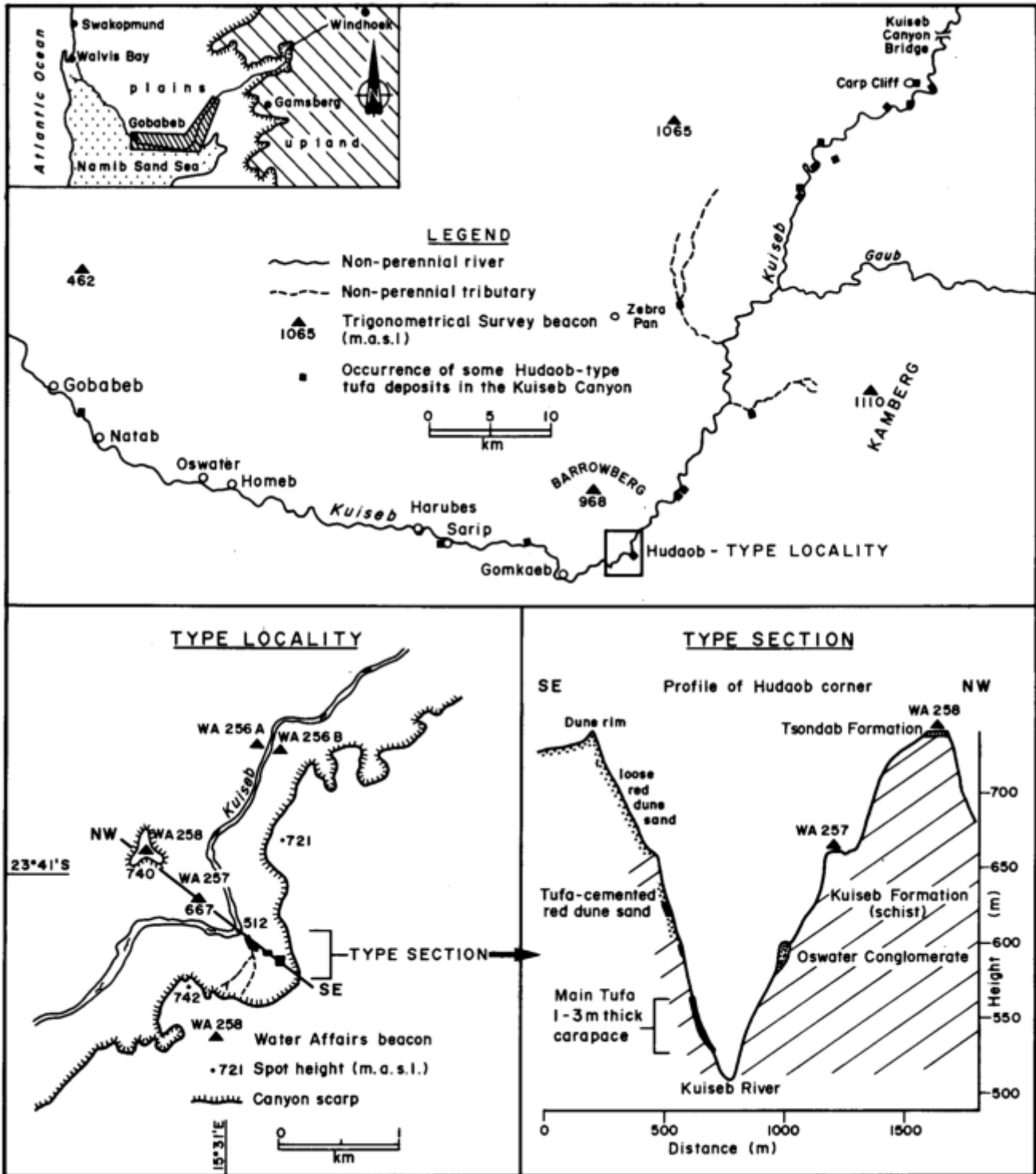


Figure 67: Distribution of Hudaob Tufa deposits in the canyon sector of the Kuiseb River. The large tufa carapace at Hudaob comprises the type locality and section for this formation.



Figure 68: Calcified vegetation (grass/sedge?) stalks included in the Hudaob Tufa exposure at the type locality. Scale 10 cm long.



Figure 69: Rounded, vesicular biogenic structures in the Hudaob Tufa exposure at the type locality. Scale 10 cm long.



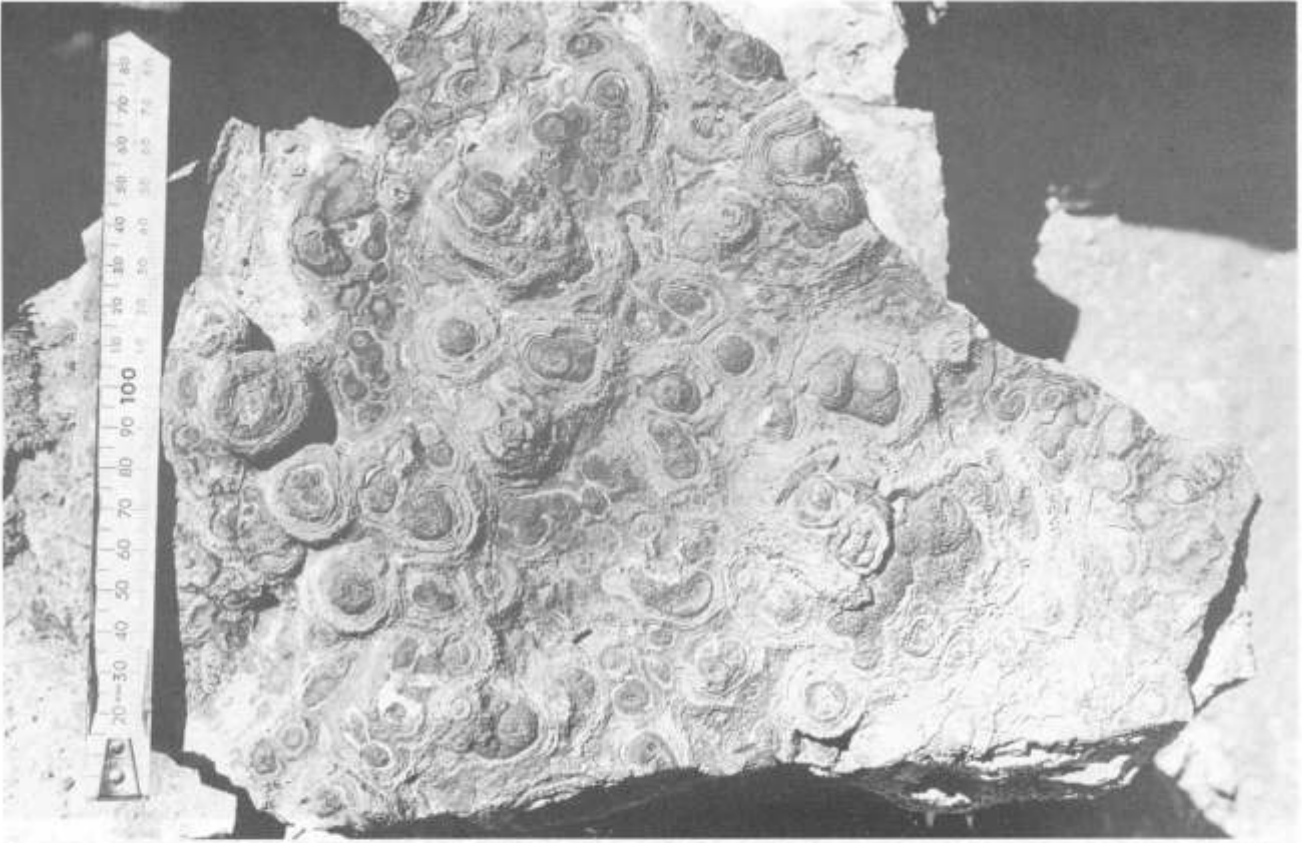


Figure 70: Low-relief, domical structures preserved on the upper surface of a travertine deposit exposed between the Kamberg and the Kuiseb canyon. Scale in mm.



Figure 71(a): Pale-coloured Hudaob Tufa carapace exposed at the type locality. Compare with Fig. 71(b).

Figure 71(b): Modern, actively-forming tufa in the Naukluft. Hammer for scale.



Figure 72: Biogenically-induced precipitation of calcium carbonate to give vesicular, rounded structures. A moss, *Barbula* sp. (inset), causes the precipitation of calcium carbonate. Modern tufa site, Naukluft Mountains. Compare with Fig. 69.

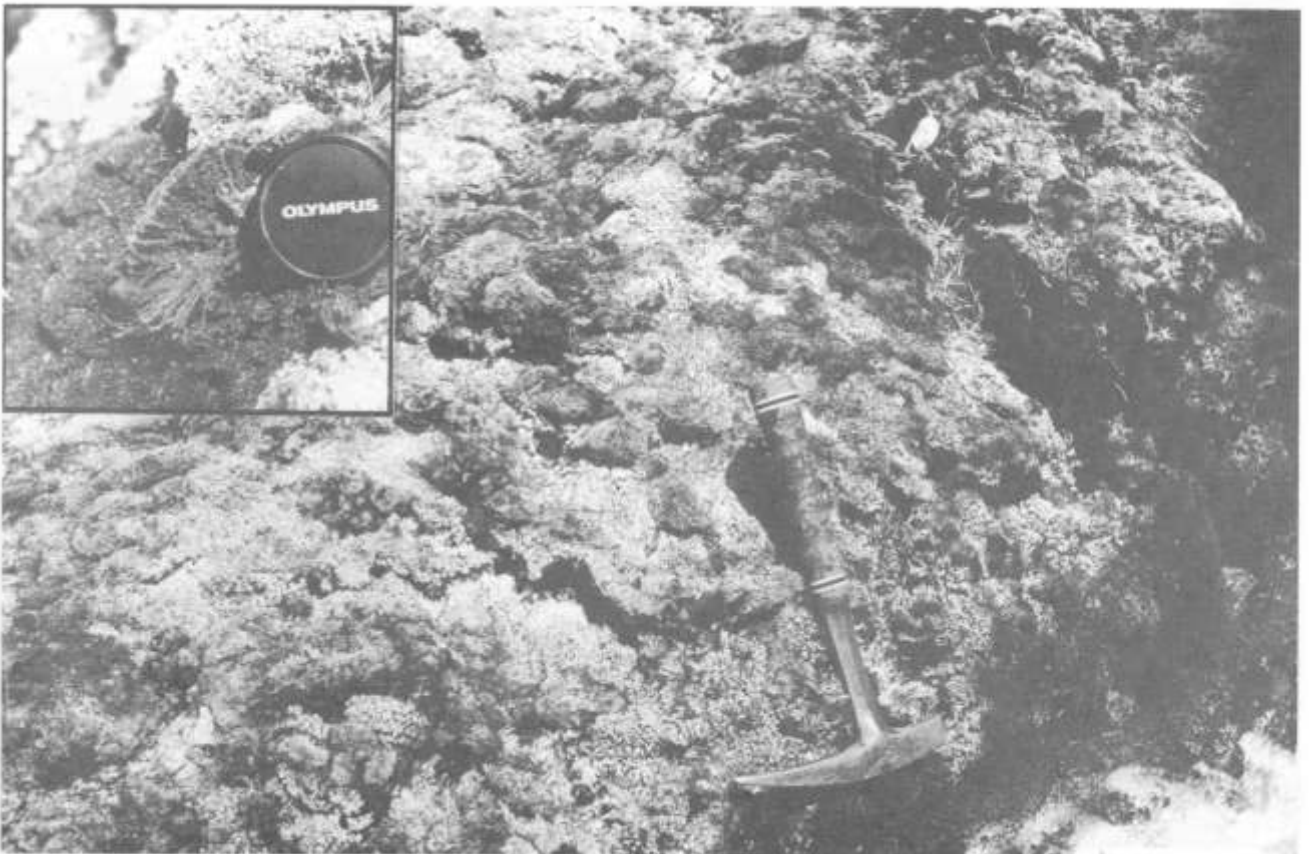


Figure 73: Replacement of plant fragments, trapped in a pothole on the modern waterfall, by calcium carbonate, Naukluft Mountains. Compare with Fig. 68.

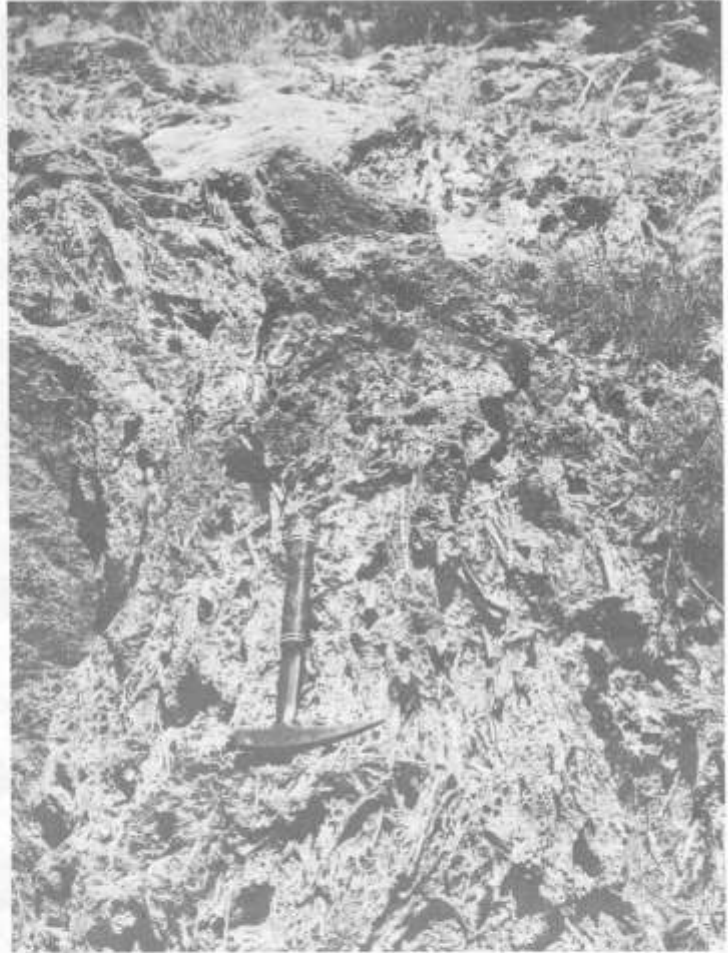


Figure 74: Large composite tufa carapace developed on the northern bank of the Swakop River canyon at the Southberg. Note reeds (*Phragmites australis*) growing on tufa below person (circled). The tufa is draped over Late Precambrian bedrock (Pc) and was active, in parts, when the site was visited in October 1981.



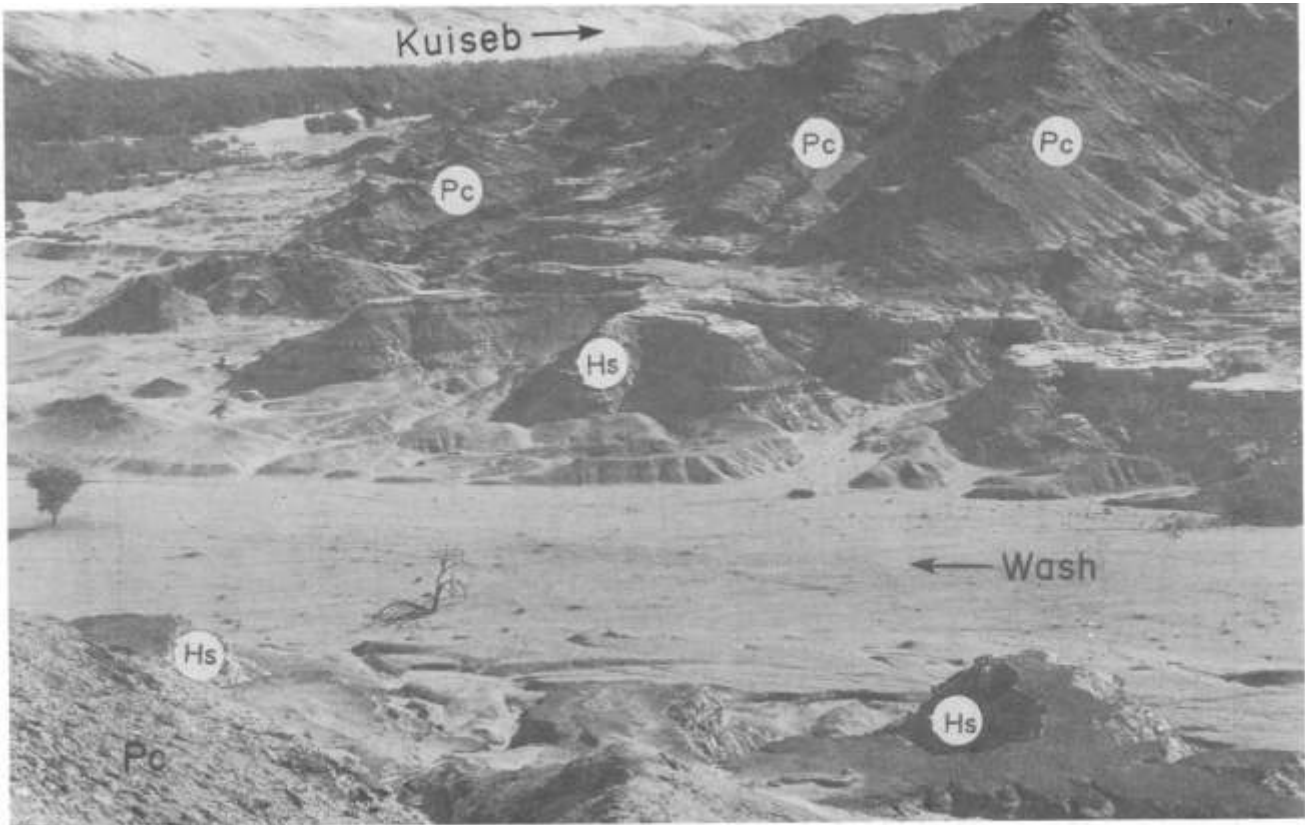


Figure 75: Flat-lying, unconsolidated silty deposits of the Homeb Formation (Hs) banked up the margins of a tributary wash and in gramadulla embayments cut into Damaran-bedrock (Pc). Silty exposure 20 - 25 m thick. View westwards down the lower Kuisseb Canyon from near Homeb towards Oswater.

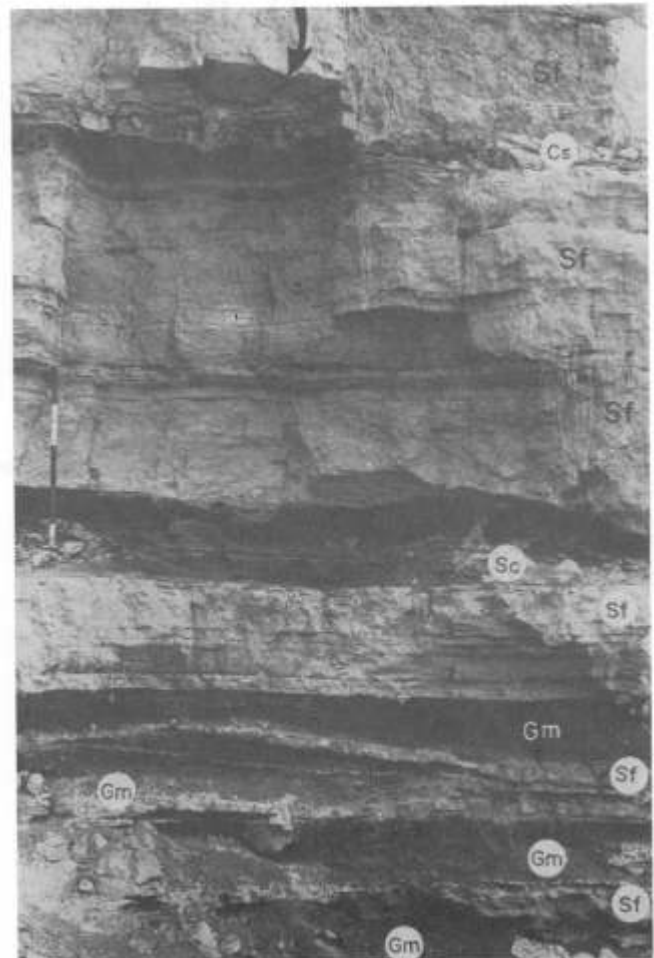


Figure 77: Homeb Silt exposure: alternation of dominant finer-grained, resistant silt layers (Sf) with lesser amounts of coarse silt (Sc) and intercalated gravel and sands (Gm) derived from the bedrock. Note desiccation crack (arrowed) in upper part of photograph. Type locality near DW 303 beacon. Scale 1 m ranging rod.



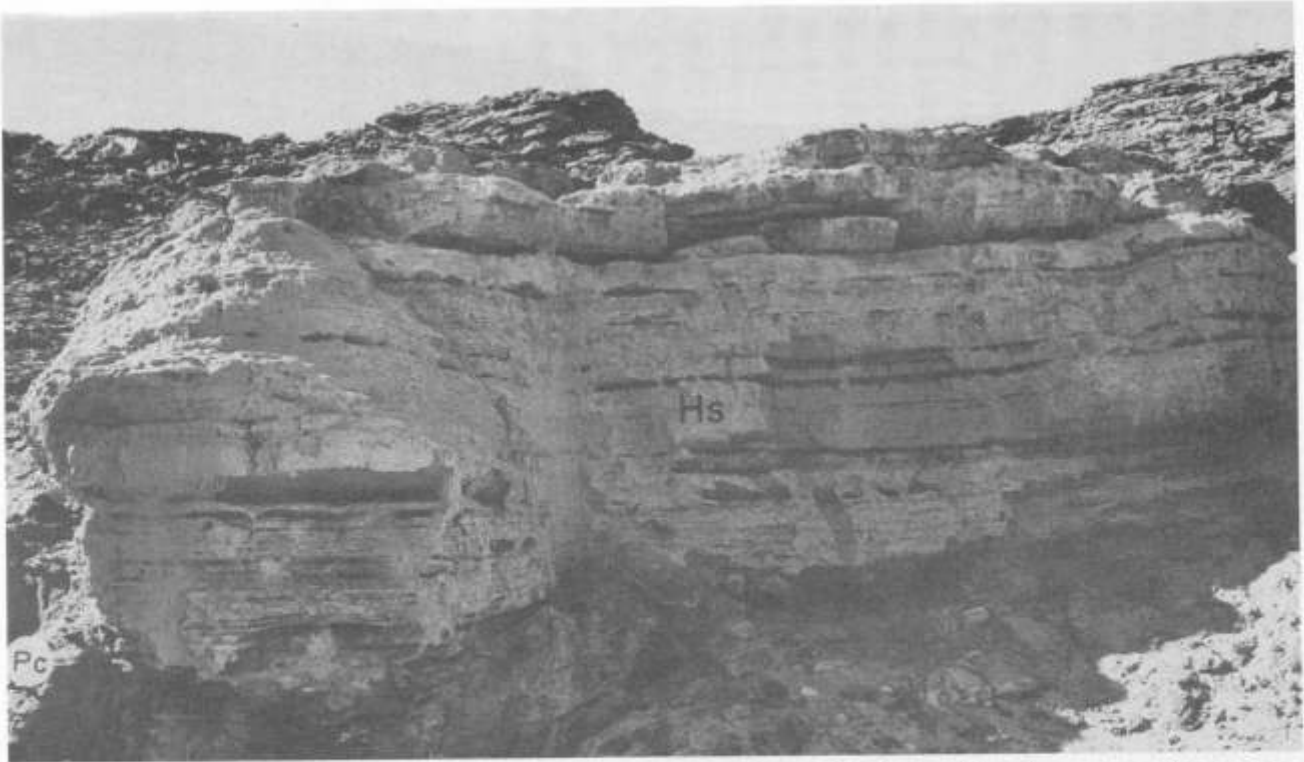


Figure 78: Irregularly alternating sequence of resistant and less resistant silt beds in a Homeb exposure (Hs) abutting Damaran bedrock (Pc). Exposure c. 5 m thick. WA 189 embayment, lower Kuiseb Canyon.

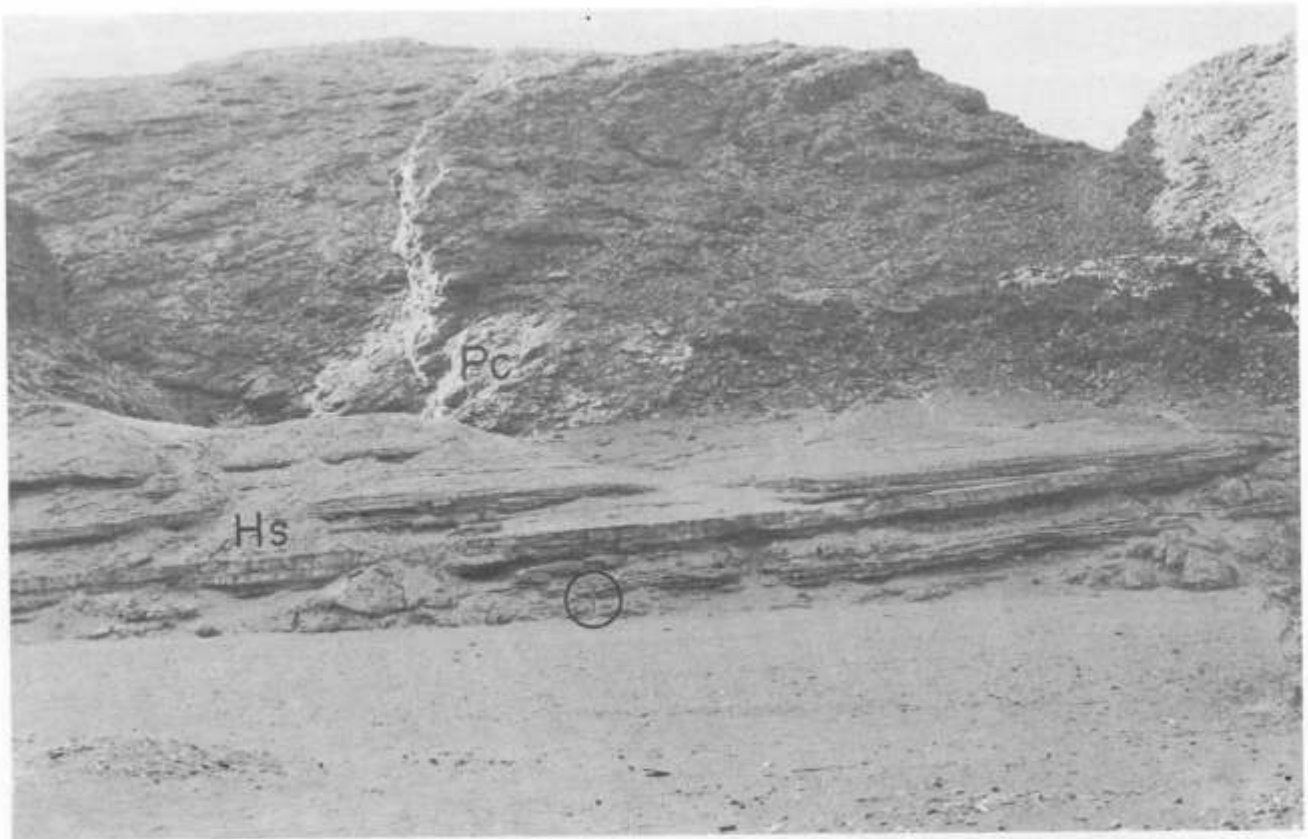


Figure 79: Layers of Homeb Silts (Hs) dipping gently away from, and roughly perpendicular to, the main Kuiseb course. Embayment in Damaran bedrock (Pc) near Awanab. Scale 1 m ranging rod (circled).

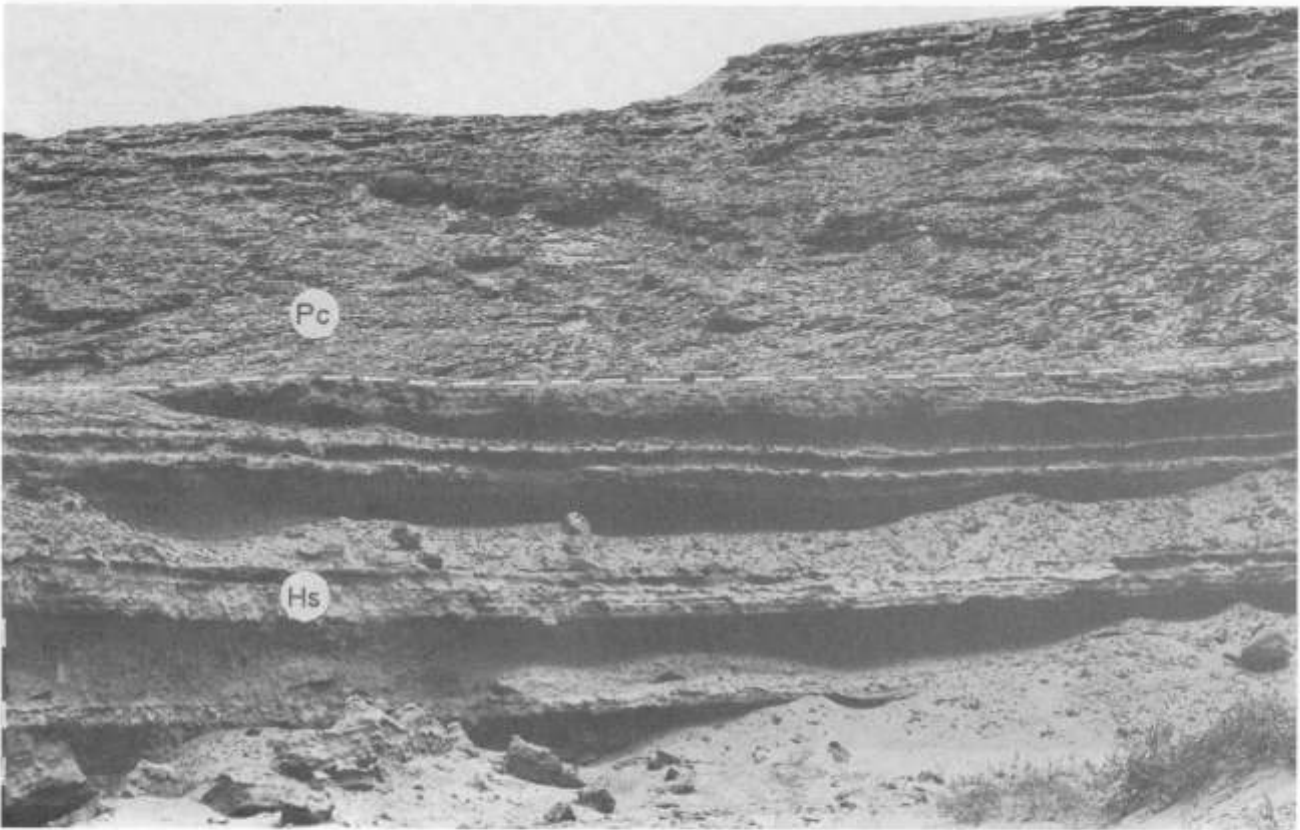


Figure 80: Regularly alternating sequence of thicker silty sand units and resistant silt beds in a Homeb Silt exposure (Hs) abutting Damaran bedrock (Pc). WA 294 embayment near Gari-goras. Scale 2 m ranging rod.

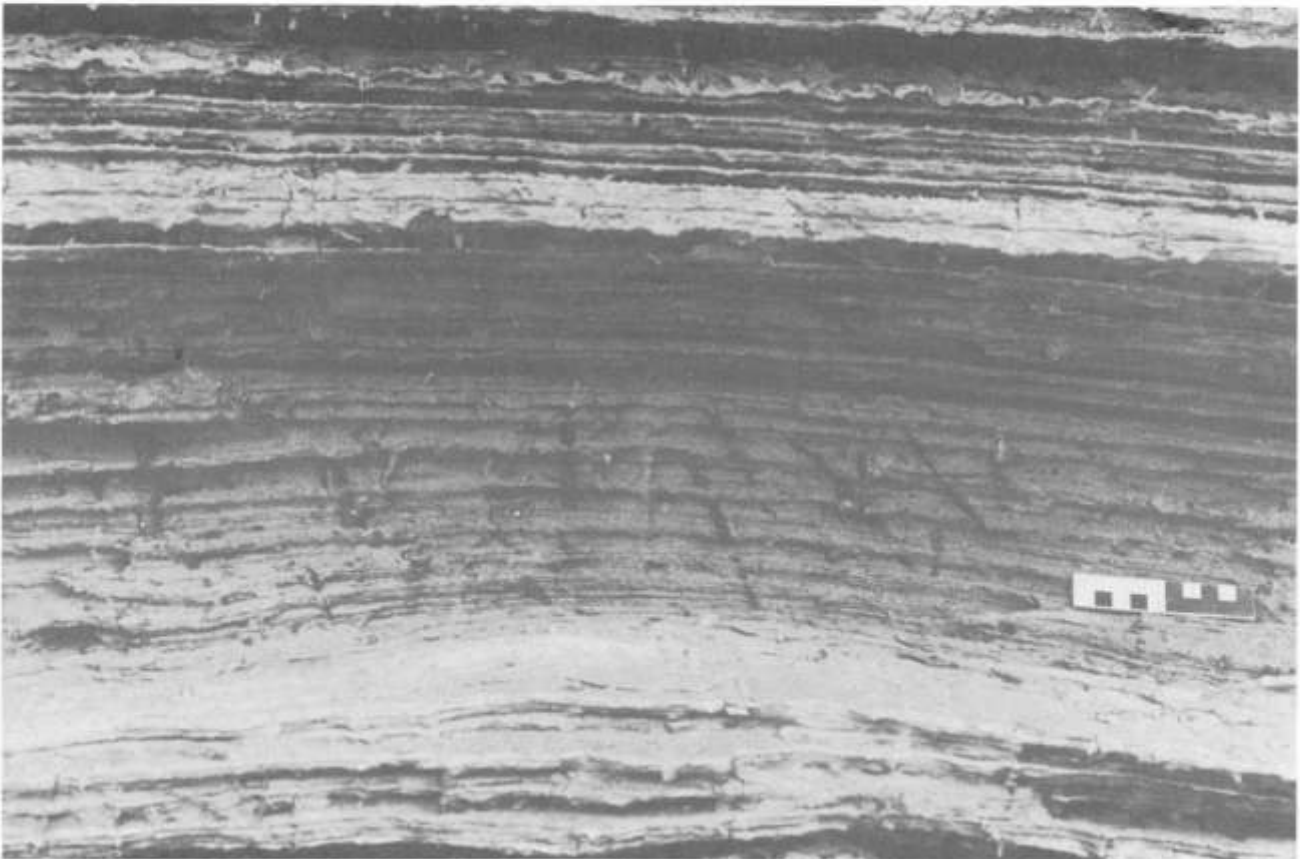


Figure 81(a): Horizontal lamination, cross-cut by oxidised root traces, in biotite/phlogopite-rich silts. Scale 10 cm long.

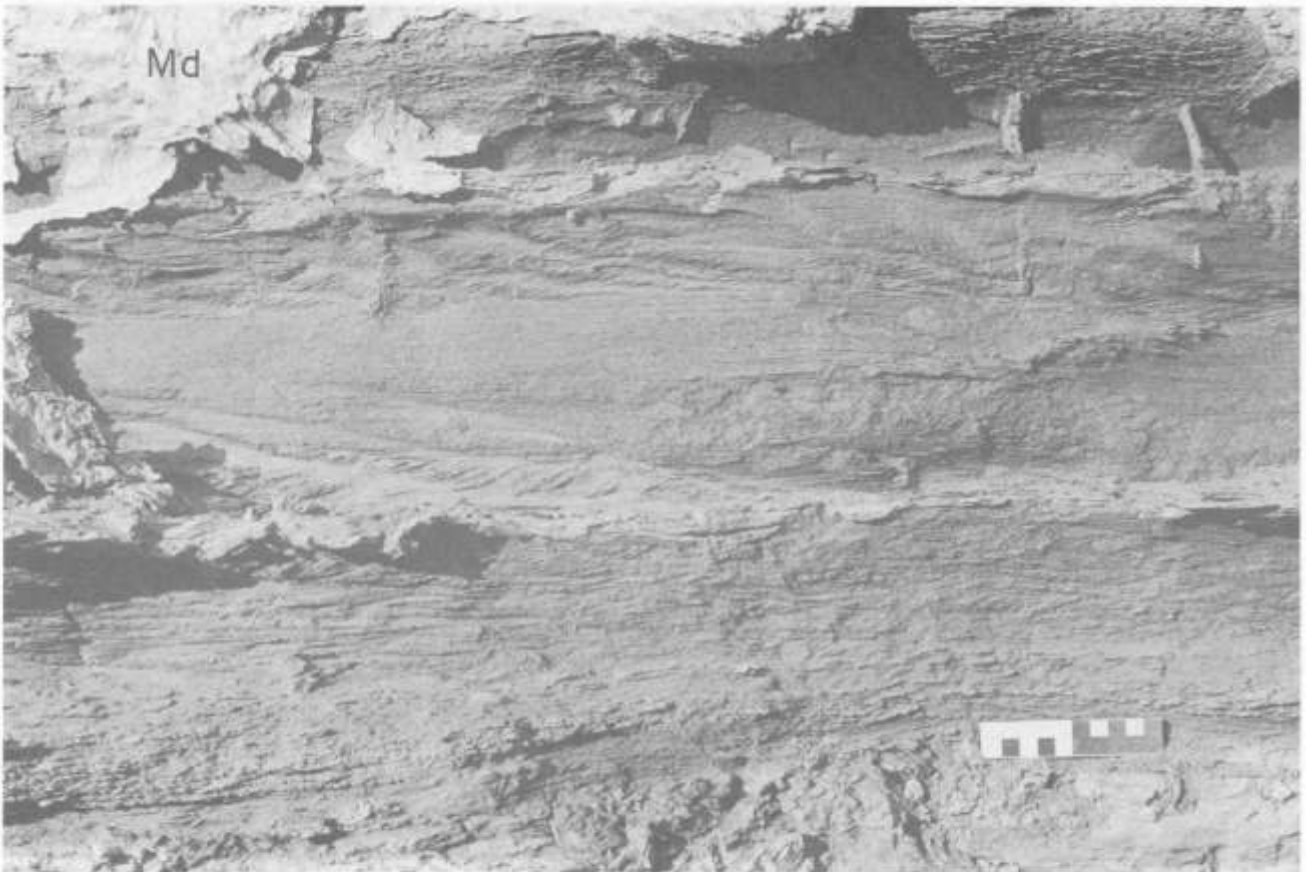


Figure 81(b): Ripple-drift cross-lamination in Homeb Silts. Secondary mud drape (Md) in upper left corner Scale 10 cm long.

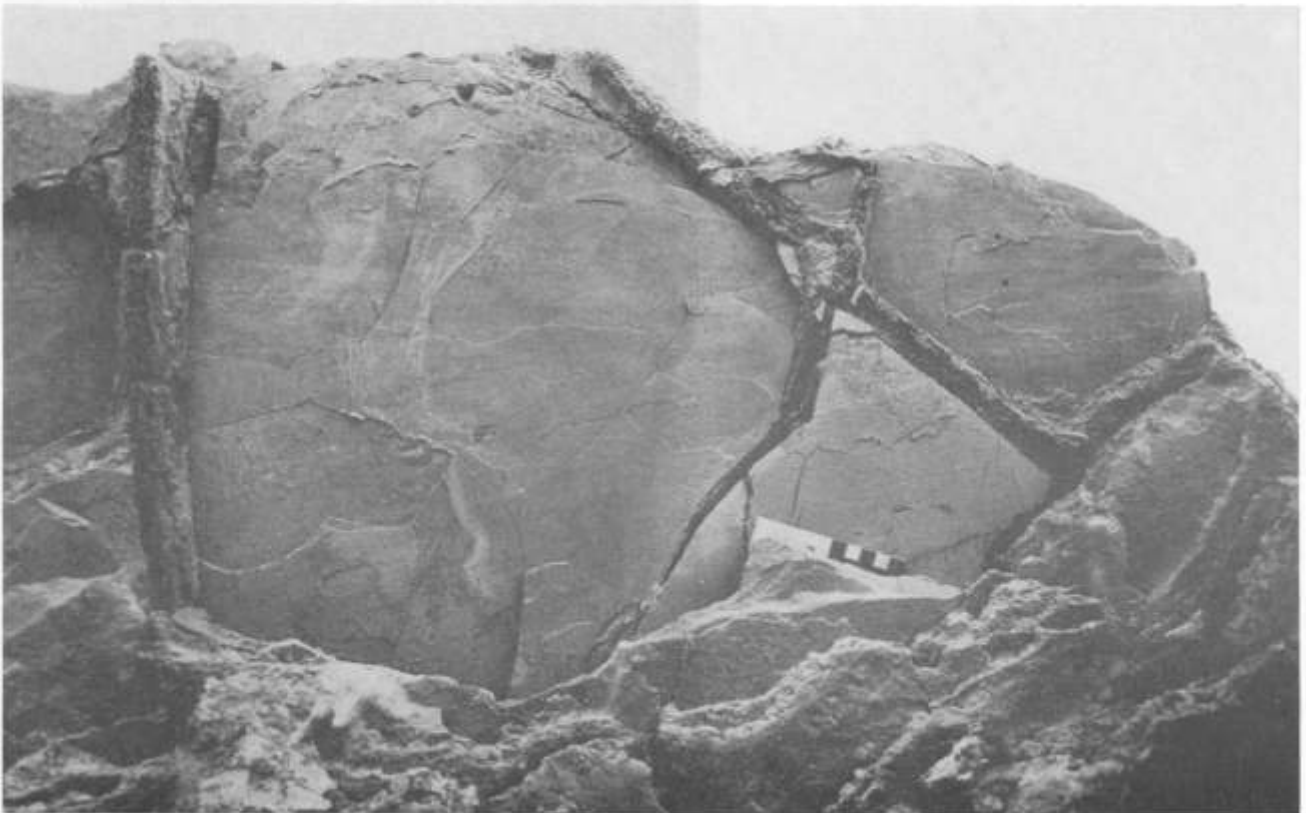


Figure 82: Desiccation cracks developed in yellowish silts and filled with silty sand. View from below. Scale 10 cm long.



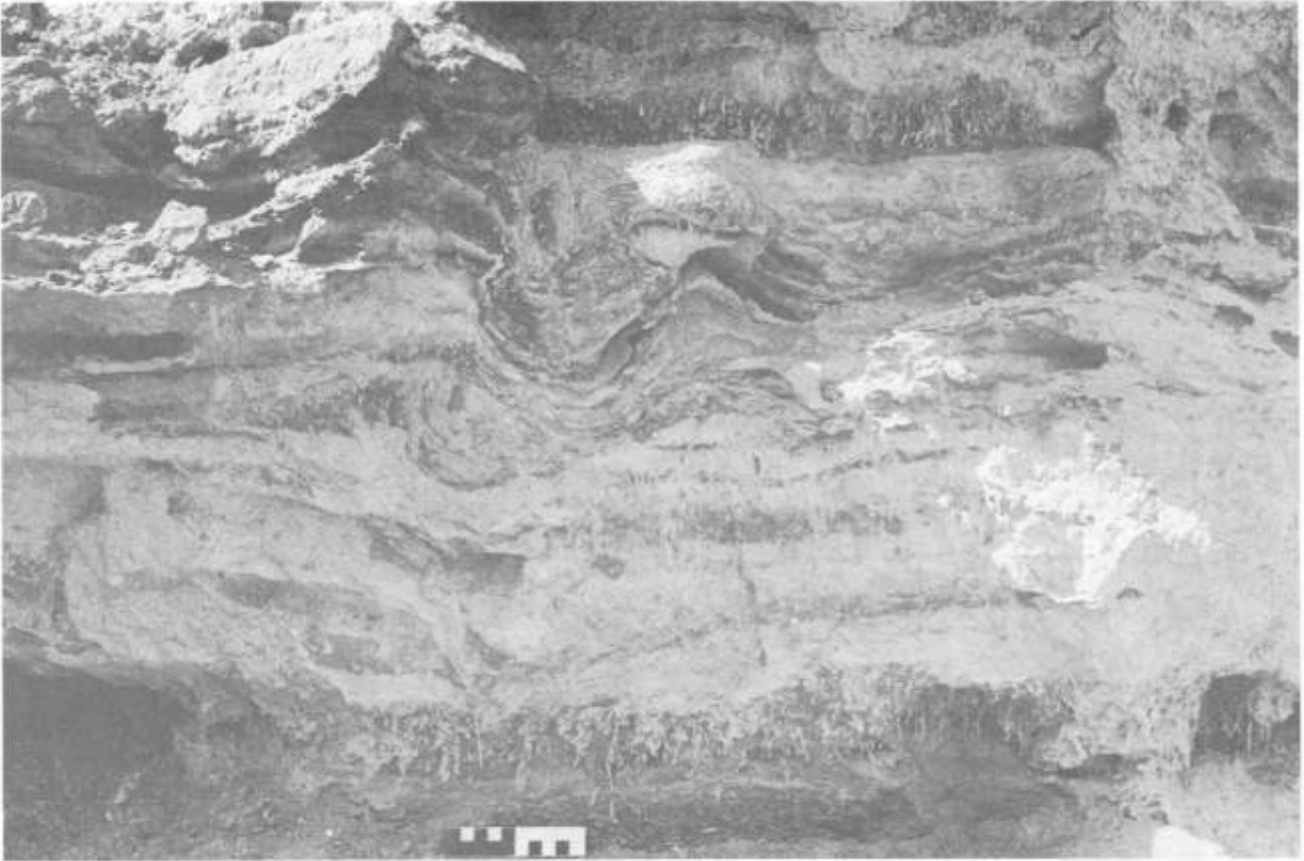


Figure 83: Convolute lamination in a silty sand bed in a Homeb Silt exposure near DW 303 beacon. Scale 10 cm long.

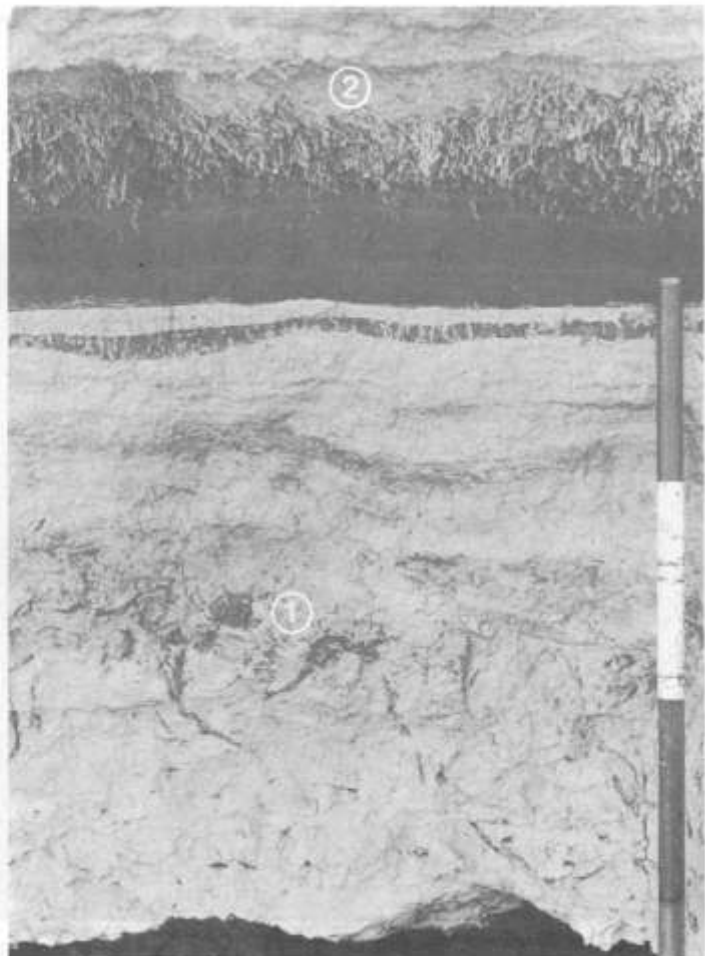


Figure 84: Oxidised traces of former plant roots (1) in a hardened Homeb Silt layer. Dense concentrations of pedotubules (2) resemble those developed around grass roots, e.g. *Cladophis spinosa*, in the modern Kuseb River bed. DW 303 - Homeb area. Scale 0,2 m intervals.



Figure 85: Horizontal (feeding ?) trails and subvertical pedotubules, which resemble burrows, in Homeb Silts at the type locality. Scale 10 cm long.

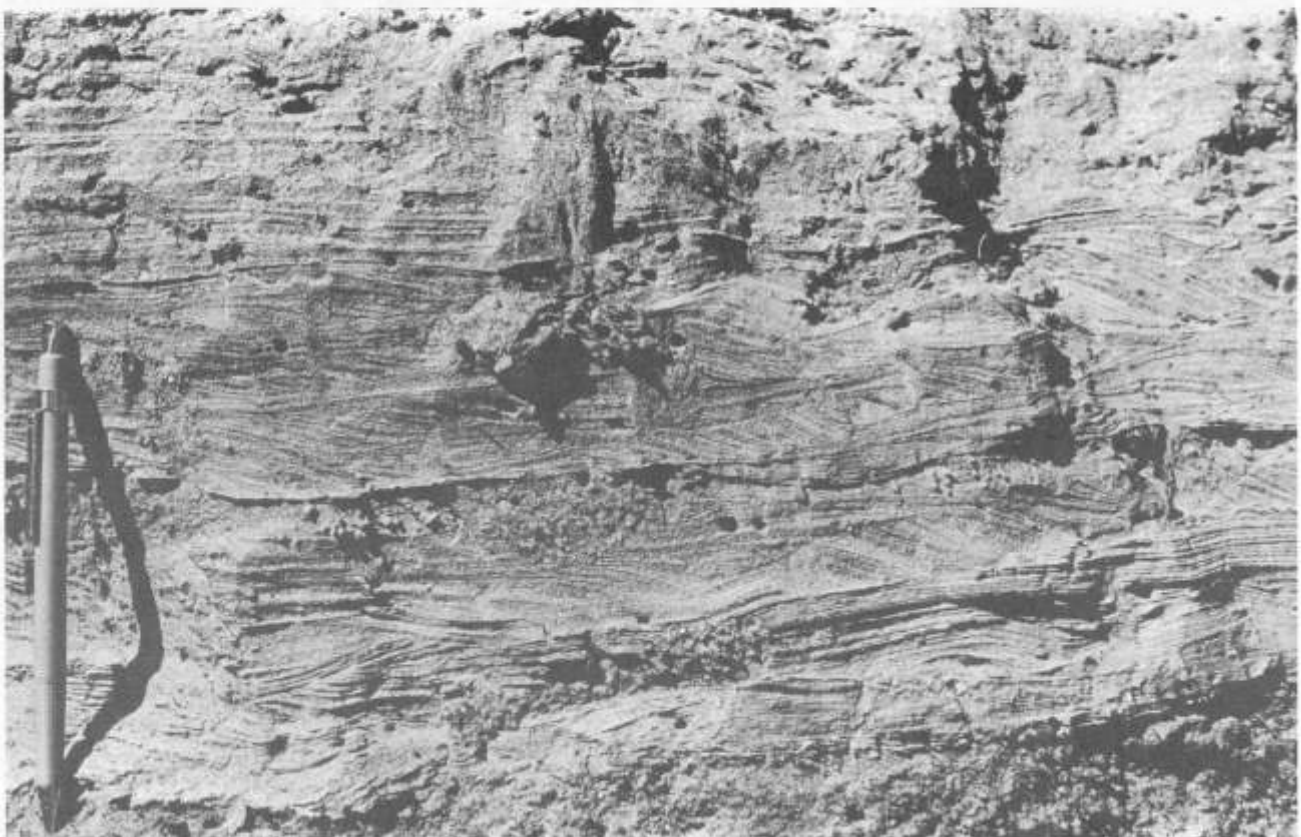


Figure 86: Micro-stratification in silty flood plain deposits of the modern Kuiseb River. Obertaem, near Gobabeb. Pencil, 15,5 cm long, for scale. Compare with Fig. 81.



Figure 87: Penecontemporaneous deformation of silty sands under a cohesive, 10 cm thick muddy silt layer in the modern Kuiseb River one day after March 1981 flood. Gorob-Kuiseb confluence. Tape for scale.

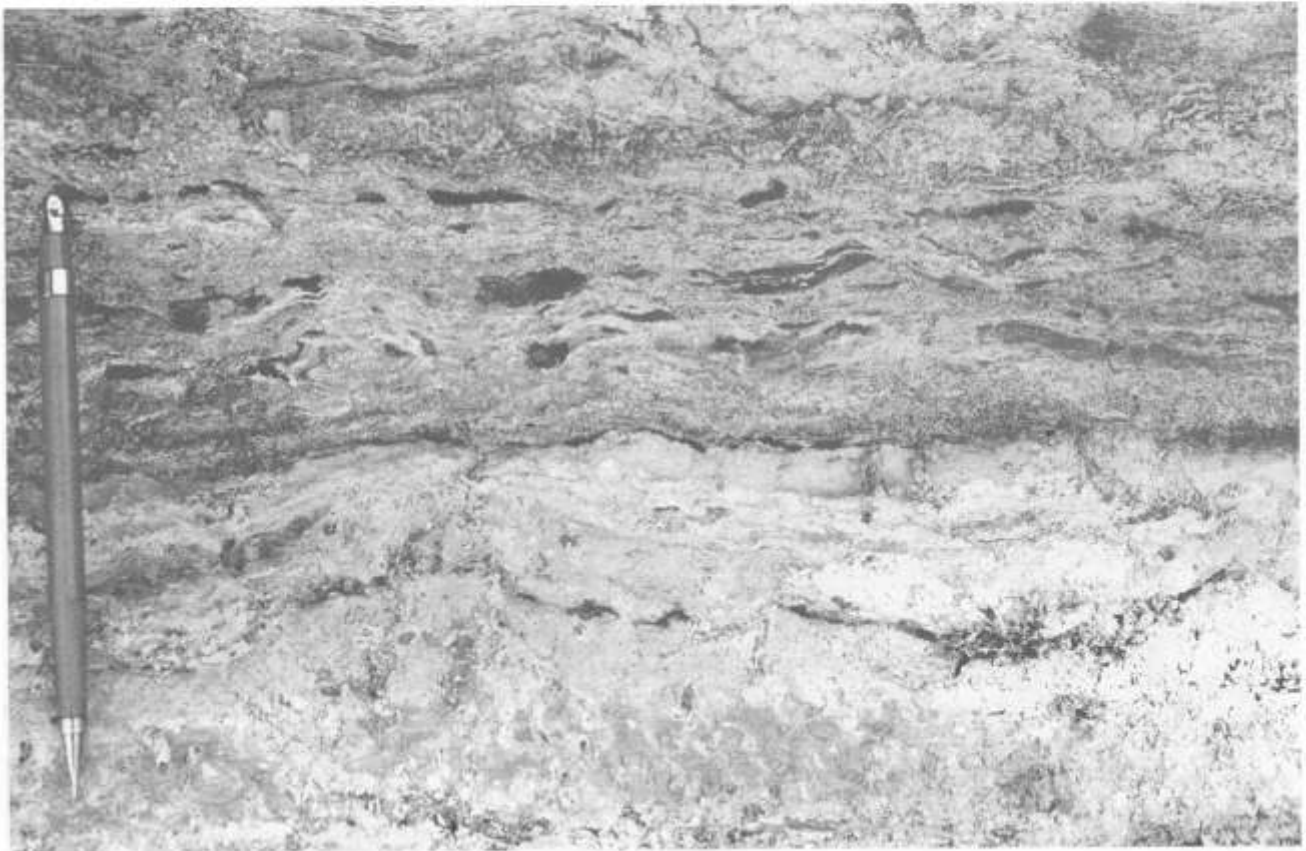


Figure 88(a): Oxidised organic layer (flotsam), relatively free of detrital sediment, in a Homeb Silt exposure between DW 306 and DW 307 beacons. Pencil 15,5 cm long.

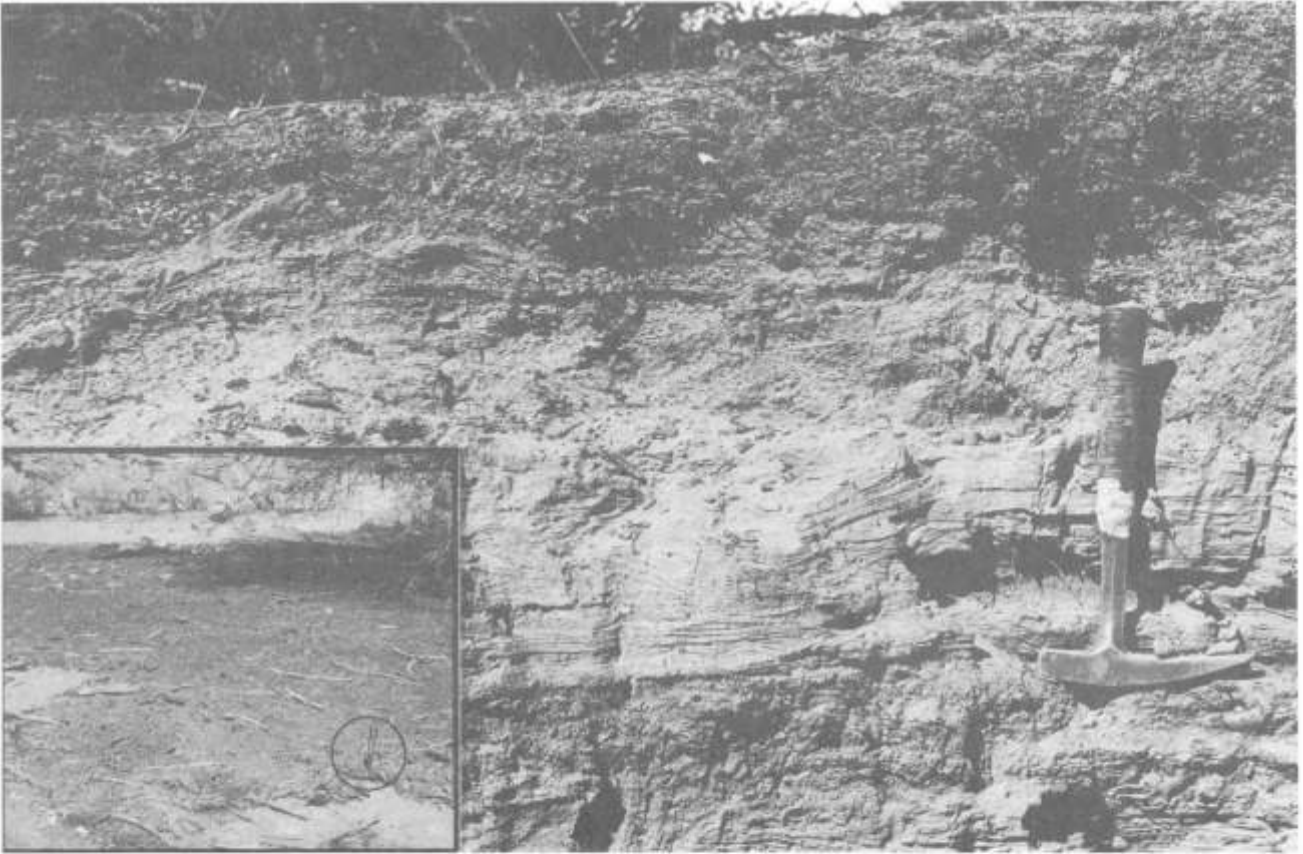


Figure 88(b): Organic litter layer deposited as flotsam on flood plains silts of the modern Kuiseb River. Inset shows modern organic flotsam deposits during March 1981 flood, Kuiseb Canyon bridge.

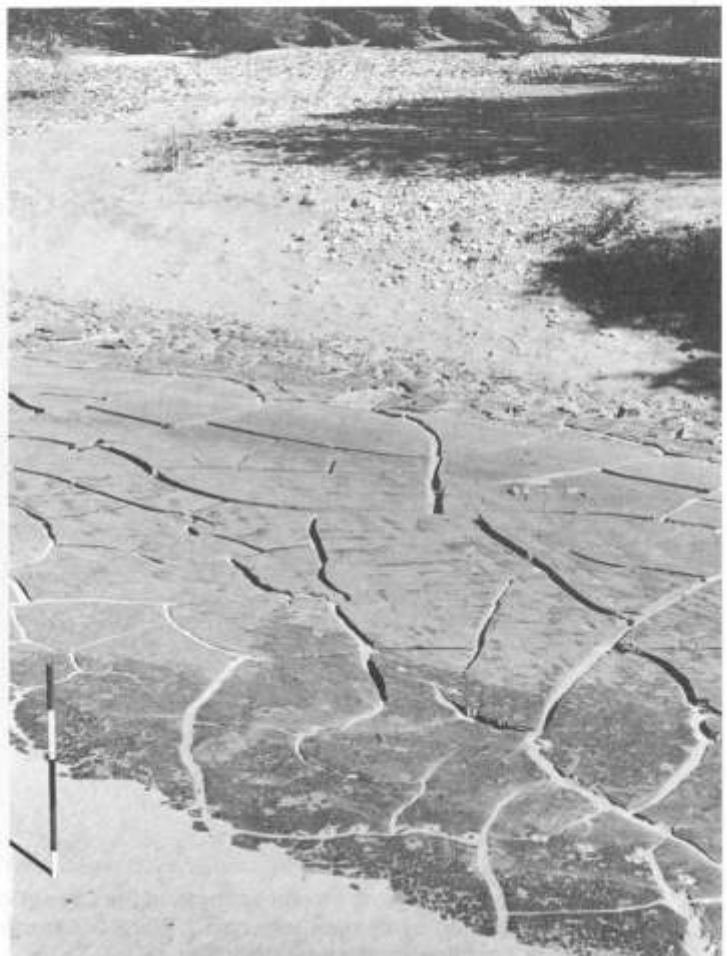


Figure 89: Desiccation cracks developed in muddy silts in the modern Kuiseb River. Wind-blown river sand partially filling cracks. Gomkaeb corner. Scale 1 m ranging rod.

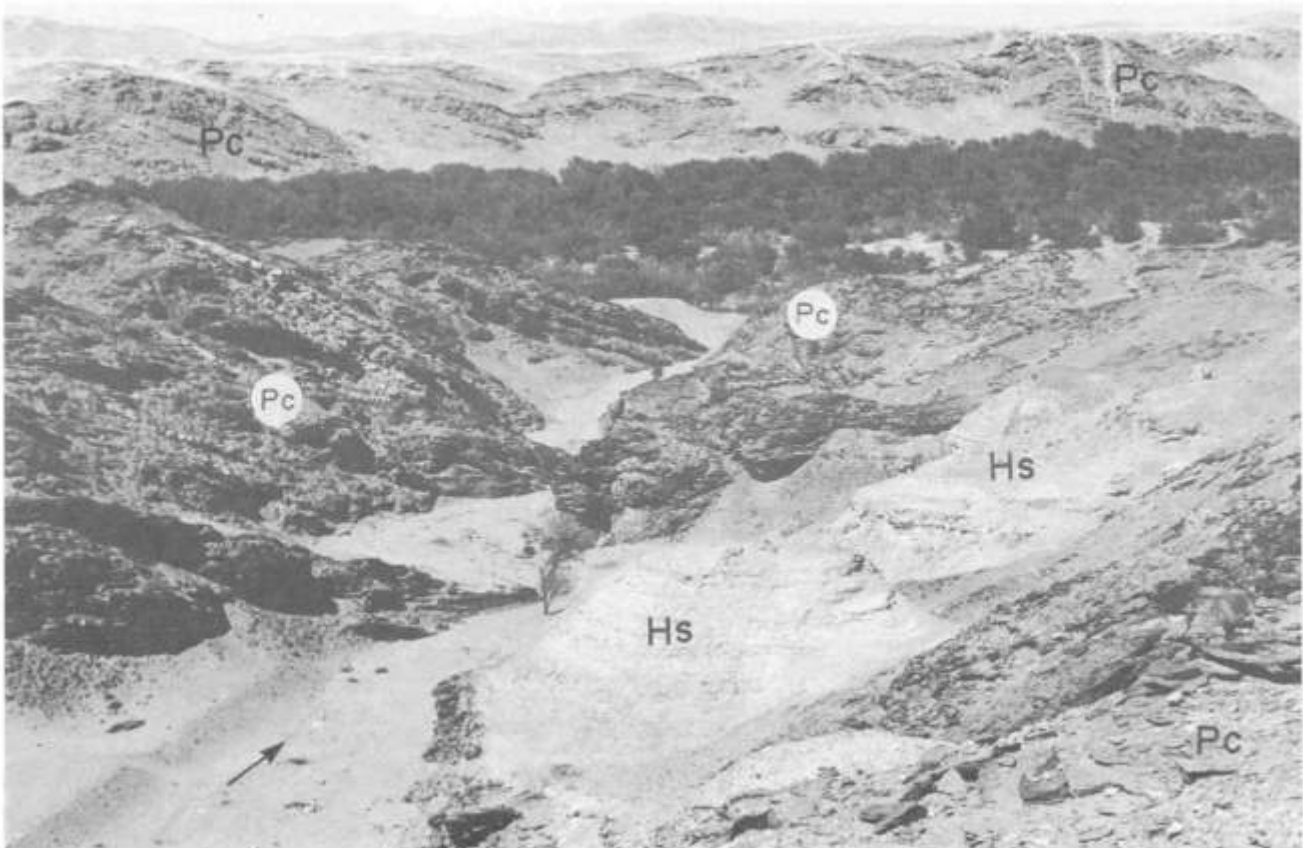


Figure 90: View down north-bank tributary of the Kuiseb River towards the main course near DW 307 beacon. Homeb Silts (Hs) c. 15 m thick, banked up c. 400 m from Kuiseb flood plain and c. 650 m from main course. Damaran bedrock (Pc) dissected to form gramadullas.

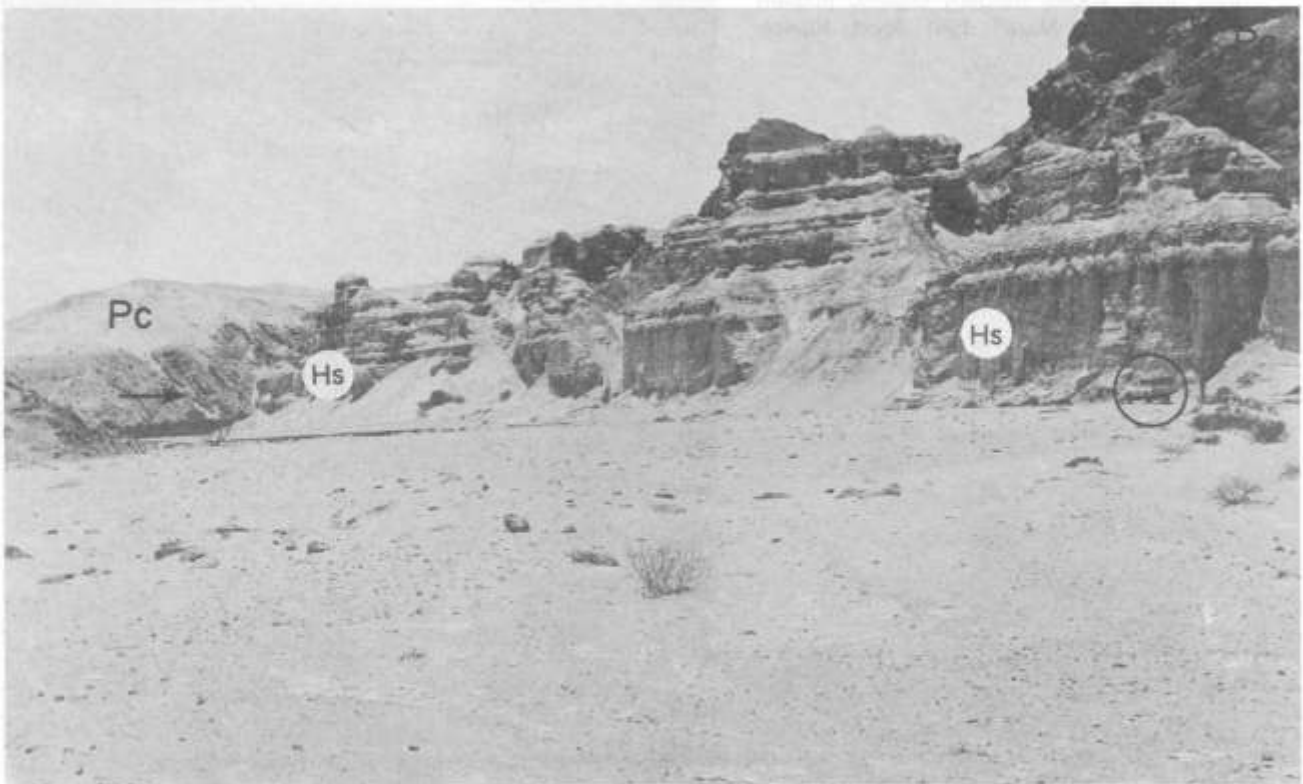


Figure 91: View down a north-bank tributary canyon of the Lower Hoarusib River, Skeleton Coast. The Hoarusib River (arrowed) is demarcated by riparian vegetation. Thick unconsolidated silty deposits (Hs) are banked up the tributary canyon cut in Late Precambrian bedrock (Pc).



Figure 92: Poorly-exposed, unconsolidated fine-grained sediment scarp of Awa-gamteb muds capped by Gobabeb Gravels (Gg). Reference locality to south of Kuiseb Project beacon, KP 110. Modern coastal crescentic dune (Ds) encroaching onto scarp. Footprints (arrowed) for scale.



Figure 94: Dark clay layers intercalated with silts and micaceous sands in the upper part of the Awa-gamteb mud exposure near KP 110 beacon. Salt veinlets in uppermost clay bed. Scale 10 cm long. Section cleaned with a shovel gives appearance of soft-sediment deformation.





Figure 95: Gypsum crystal aggregates ("desert roses") forming a thin horizon in Awa-gamteb muds. Mile - 10 Reservoir area. Scale 10 cm long.



Figure 96(a): Crescentic dune (hammer of scale) planed by Kuiseb floodwaters and partially consolidated. Bg 2/77 area, Kuiseb Delta. White sands of present-day dunes in background have been semi-stabilised by *Tamarix usneoides* trees.





Figure 96(b): Elephant (*Loxodonta africana*) tracks in fluvial silts capping planed dune sands (not visible) near Rooibank. Desiccation cracks well developed.



Figure 97: Part of the unconsolidated sediment wedge, up to 40 m high, exposed in the Unjab "Delta", Skeleton Coast. View northwards. Gravels in right foreground.

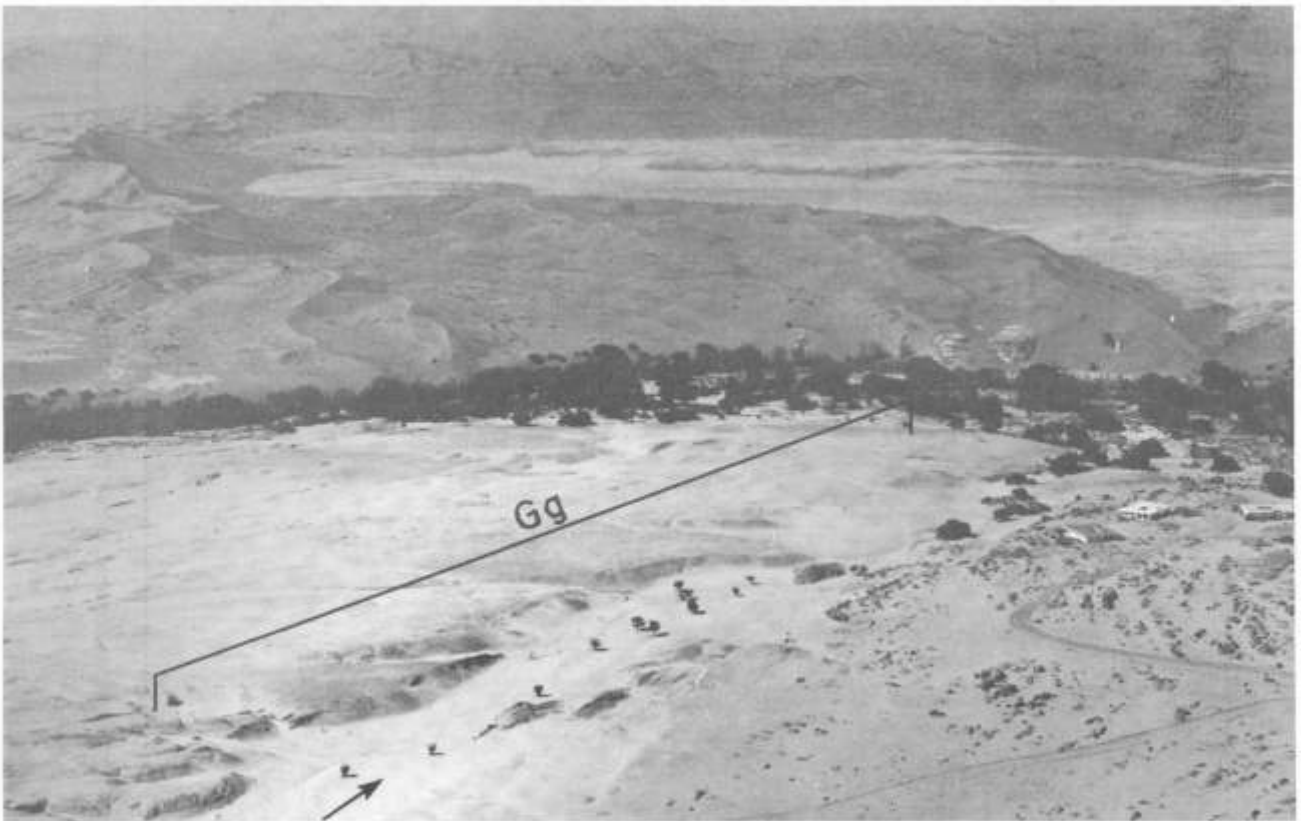


Figure 98: Oblique aerial view southwards of the type locality (Gg) of the Gobabeb Gravel Formation near the Namib Research Institute at Gobabeb. Kuiseb River in middle-ground with linear dunes along southern bank.



Figure 99: Resistant, rounded clasts in a Gobabeb Gravel terrace deposit near DW 303 beacon, Homeb. Water-worn boulder of Oswater Conglomerate next to hammer in right foreground.



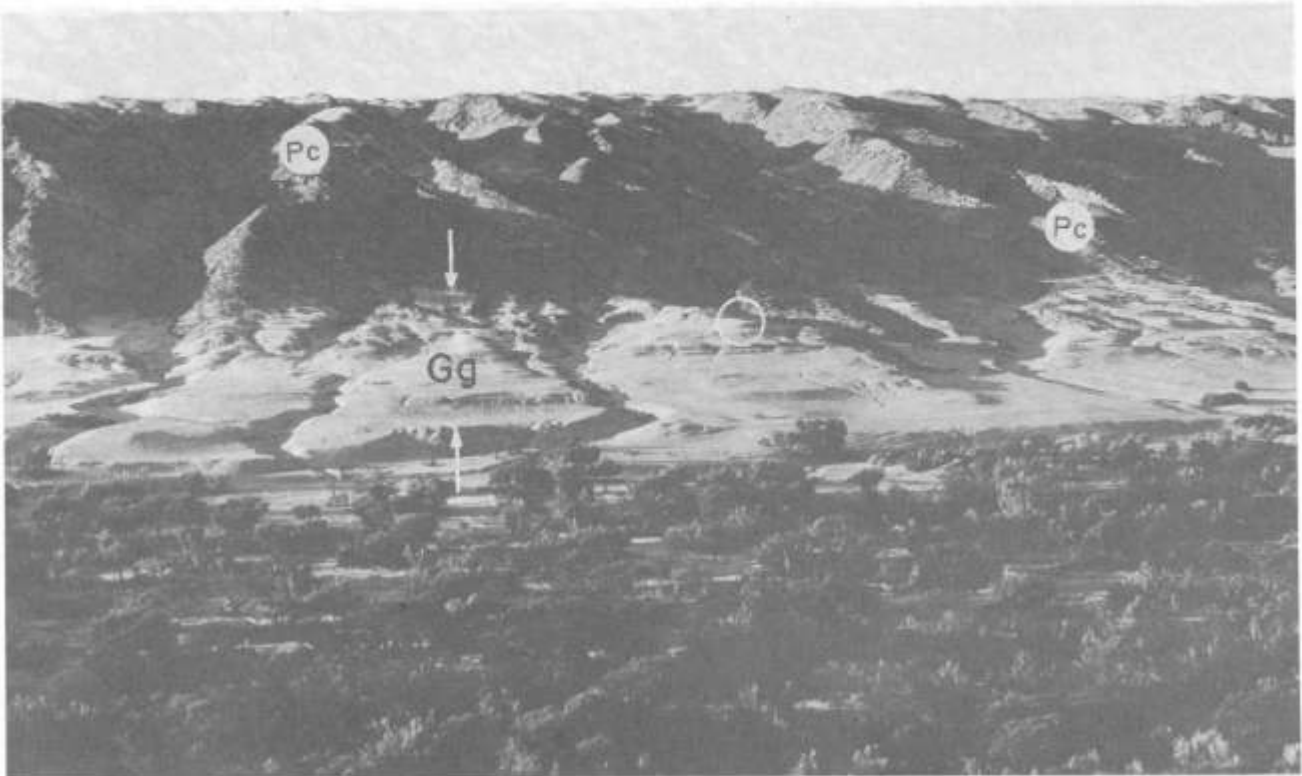


Figure 101: Stepped suite of Gobabeb Gravel-capped terrace levels from c. 5 m to c. 30 m above the present Kuseib flood plain (arrowed). Gobabeb gravels overlie Homeb Silts. DW 302 beacon (circled) area between Dawetaraes and Homeb, view northwards over Kuseib Valley.

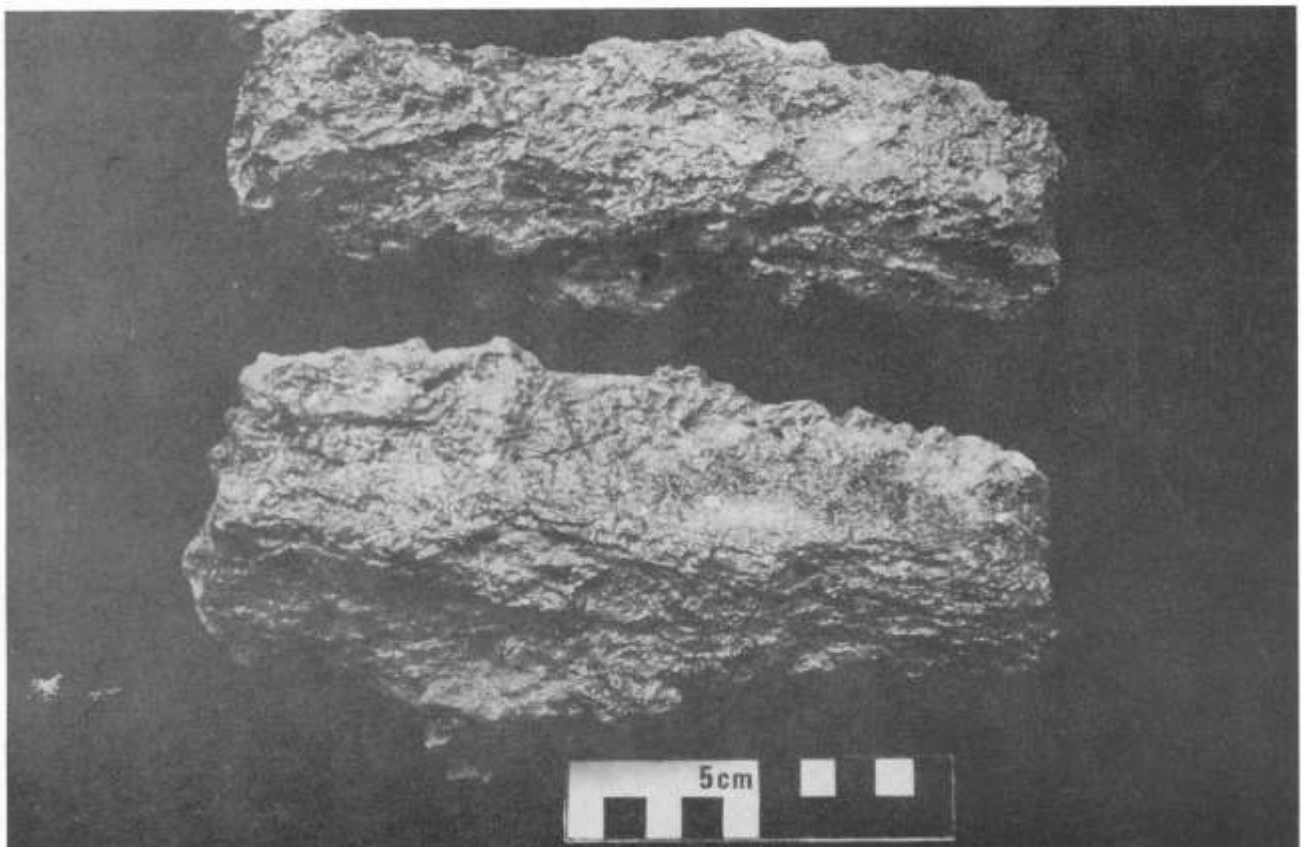


Figure 102: Water-worn pedotubules, probably calcified roots of *Acanthosicyos horrida* (Inara), DW 310/B beacon - Nataba area. The polished, weathered appearance is characteristic of carbonate-rich clasts exposed in terrace deposits within the main Namib Sand Sea.

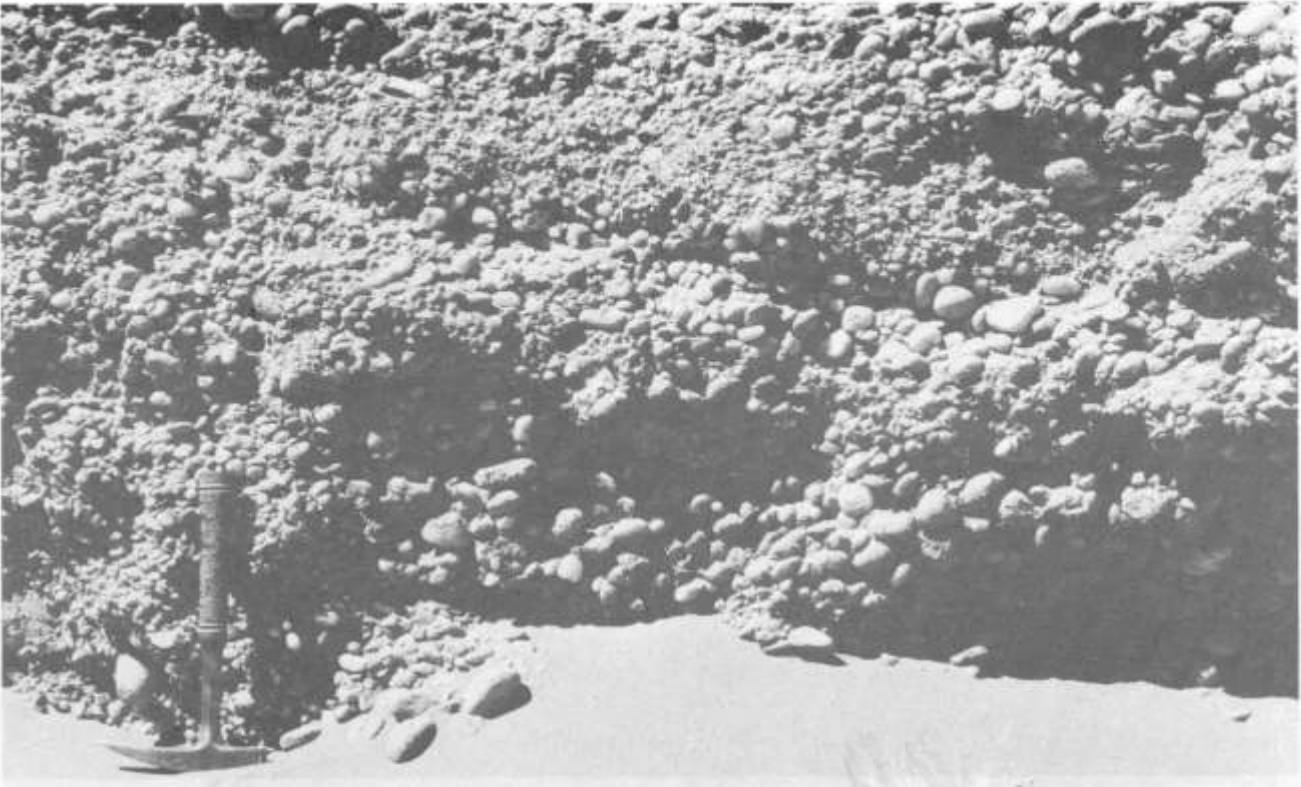


Figure 103: Cross-bedded Gobabeb Gravels, Aub - KP 10 beacon area, lower Kuiseb canyon. The well-rounded to rounded clasts, predominantly vein quartz, have been mostly inherited from the Karpfenkliff and Oswater Conglomerate Formations, thus owing their shape to previous abrasion.



Figure 104: Vesicular, carbonate-rich layer formed under a stable lag of Gobabeb Gravels. DW 302 beacon area, between Dawetaraes and Homeb. Scale in cm.



Figure 105: Gobabeb-type gravels (Gg) overlying finer-grained Homeb-type silty deposits (Hs) in the Lower Hoarusib River. Late Precambrian bedrock (Pc) comprises the steep canyon walls of the Hoarusib River. Leyland Drift, Skeleton Coast.



Figure 106: Oblique aerial view south-westwards of a carbonated deposit (arrowed) in an interdune valley of the main Namib Sand Sea. This exposure, c. 6 km north-west of Gobabeb, is the type locality of the Khommabes Carbonate Member of the Sossus Sand Formation. Kuseb River in foreground.



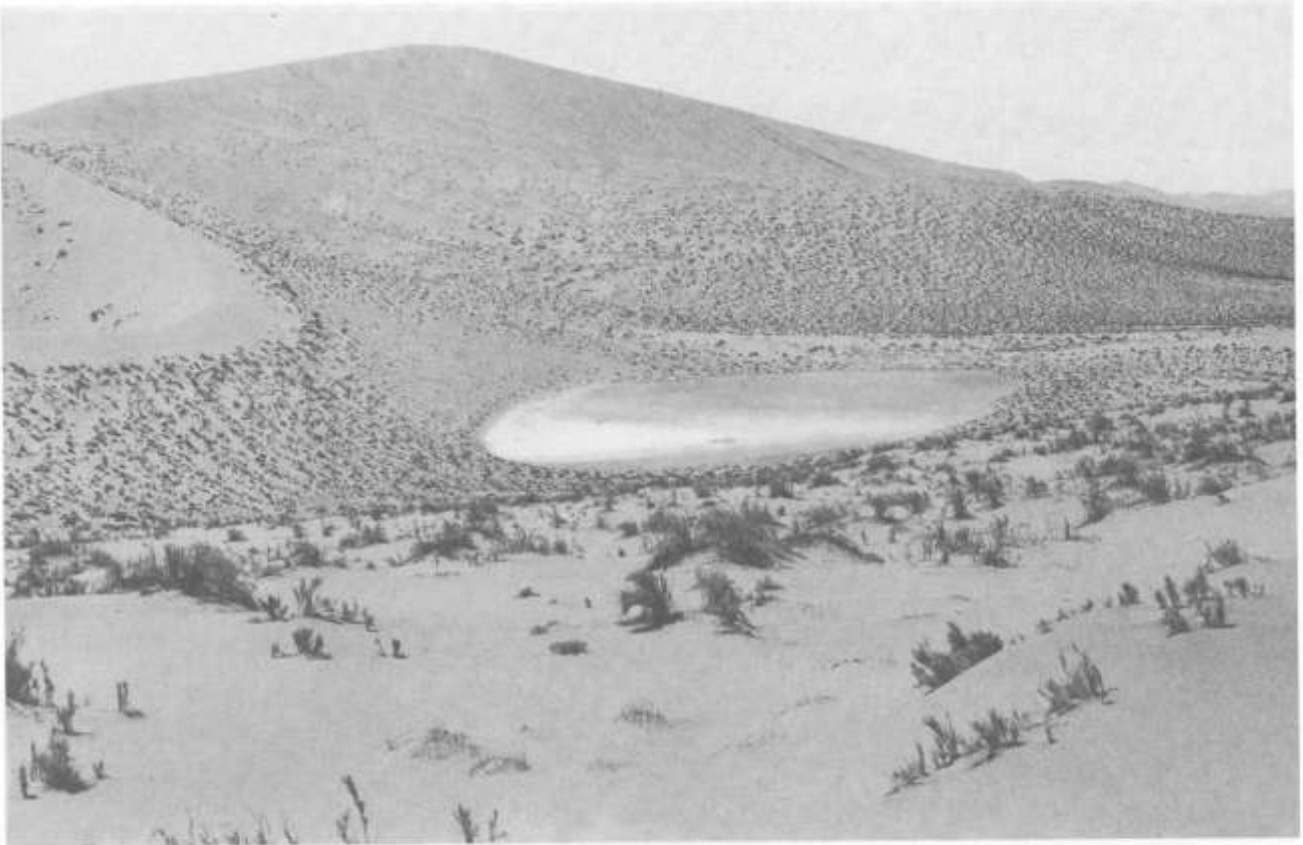


Figure 108: Distinctive, pale-coloured deposit of Khommabes Carbonate, c. 70 m long, in an interdune hollow c. 8 km south-west of Harubes.



Figure 109: Oblique aerial view south-eastwards of the mesa near Carp Cliff (WA 150 beacon area). Shallow depressions (pans) developed in a Kamberg Calcrete duricrust are considered time equivalents of the Khommabes Carbonate.



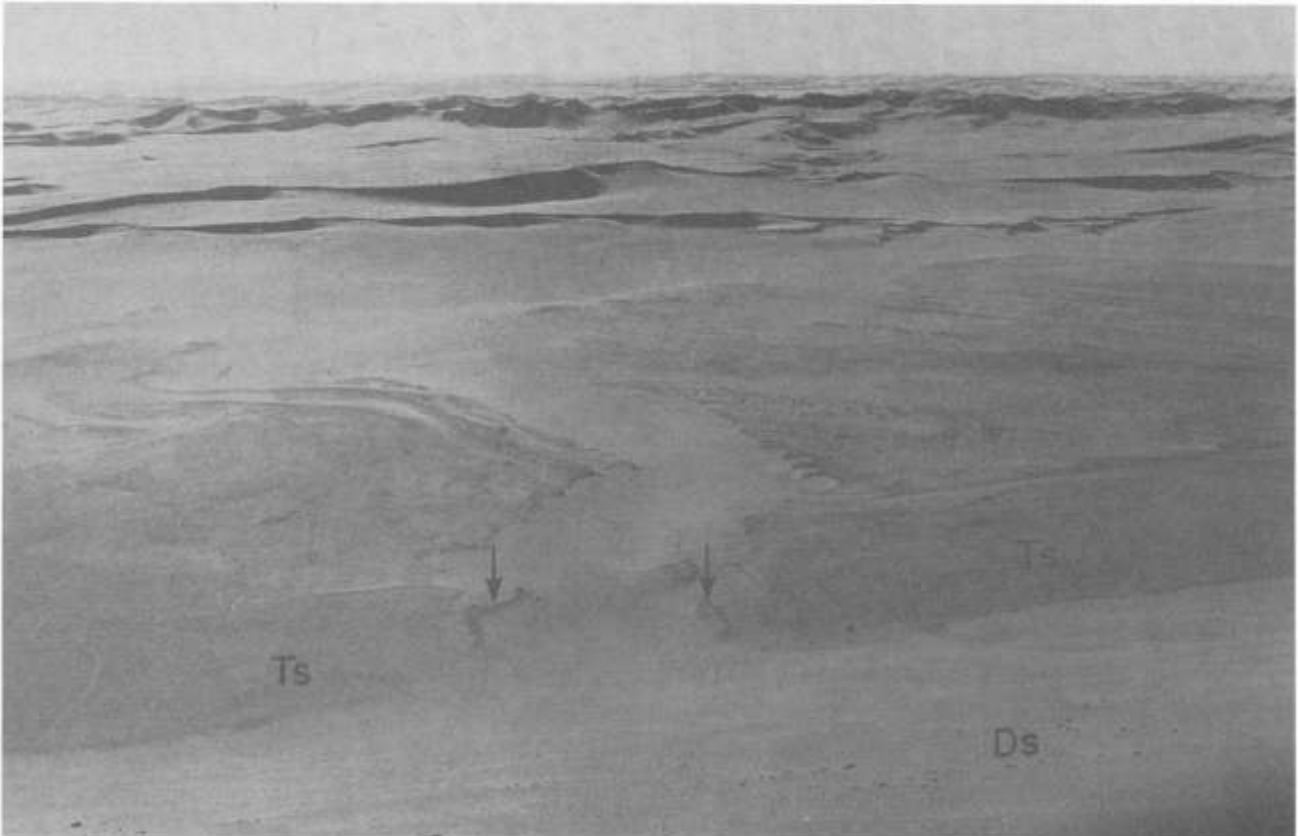


Figure 110: Oblique aerial view westwards of Khommabes Carbonate deposits (arrowed) flanking a portion of a macrofracture developed in Tsondeb Sandstone (Ts). Dune sand (Ds) of western slope of a linear dune in foreground. Interdune valley c. 20 km west of Gobabeb.

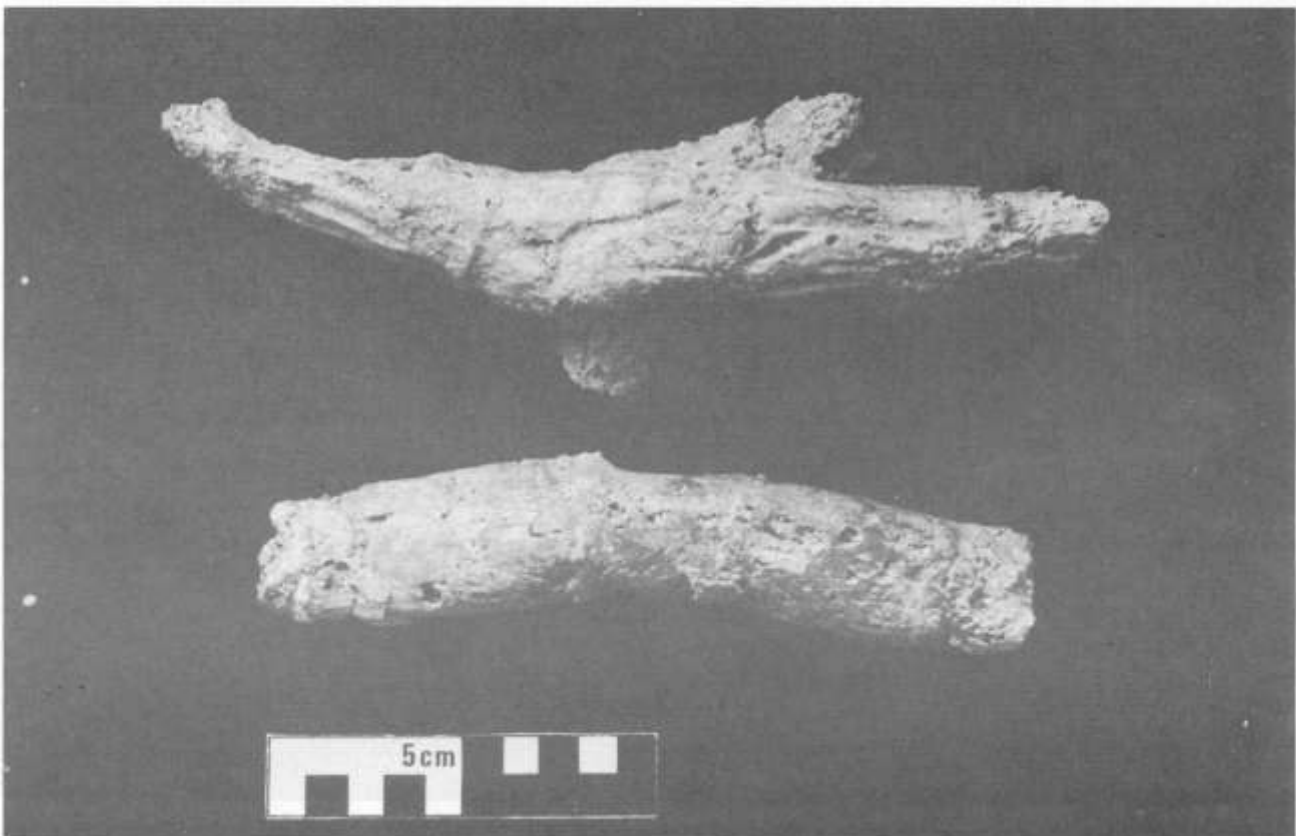


Figure 111: Calcified basal portion of reed stalks, probably *Phragmites* sp. (Photo: C.J. Ward)



Figure 112: Large-scale cross-stratification in lightly-cemented arenites on the north-western margin of the Khommabes Carbonate type exposure. Intricate biogenic structures, composed of cemented quartz sand grains, cut across inclined foresets. Hammer for scale.

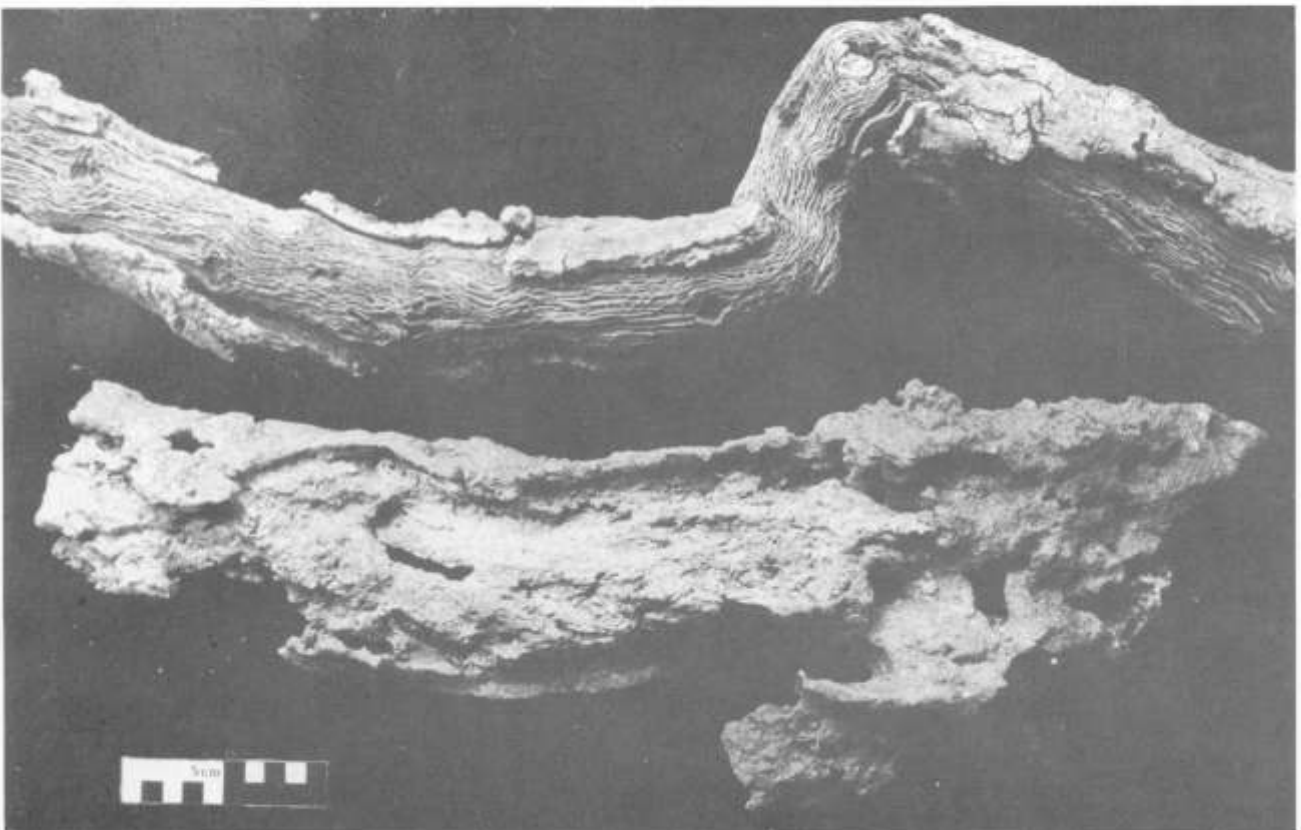


Figure 113: Comparison between a modern *Acanthosicyos horrida* root (upper fragment) and a calcified pedotubule (lower fragment) which closely resembles an *A. horrida* (*Inara*) root. Both these structures were collected from the southern margin of the type exposure at Khommabes. (Photo: C.J. Ward).



Figure 114: Shallow pool at the Gemsenwasser springs, Koigab River, Skeleton coast (Northern Namib). Algae encase pieces of vegetation and the basal portions of reeds (*Phragmites australis*) within the water body providing a modern analogue for the calcified reed stalks found in some Khommabes Carbonate deposits (Compare with Fig. 111).



Figure 115: Northern rim of a palaeo-pan deposit near the endpoint of the Koigab River, Sperrgebiet, Southern Namib.