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Origin and Surface Form of the Tsondab Sandstone Formation, Central Namib Desert

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ABSTRACT

Problems arising from a disparity in viewpoints regarding the surface form of the Tsondab Sandstone Formation, central Namib desert, Namibia, are examined through literature review and field investigation. It is shown that large distal low-angle fans, proposed in what has been termed the Low-Angle Fan Model, are absent or limited to proximal reaches of the study area. The depositional sequence identified in what has been termed the Axial Deposition Model along the Kuiseb River in the northern part of the study area is safely applicable to the rest of the study area. Further, new deposits of the Tsondab Sandstone Formation are identified. The problem of the age of the Namib desert in its fossil and active forms is discussed. The processing of satellite images is used and is shown not to be a viable technique for the identification of sedimentary bodies which are partly mantled by deposits of sediments of a similar nature.

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

________________________________.

26th day of October, 1990.

For my parents
to whom I owe
more than I could ever repay

Because I sought it far from men,
In deserts and alone.
(Kipling, *The Naulahka*)

PREFACE

Tertiary sedimentary deposits are of limited extent in southern Africa. The Tsondab Sandstone Formation of the central Namib desert, Namibia, is therefore of considerable interest. Several problems exist concerning the dating of these deposits, and their surface form.

In this dissertation the central focus is an examination of the surface form of the Tsondab Sandstone Formation through field investigation and literature review, in an effort to resolve disparities between the Low-Angle Fan Model and the Axial Deposition Model.

Chapter 1 sets the spatial context for the study, and includes a brief review of the problem and objectives of the current study as well as defining the study area. Chapter 2. comprises a review of previous work undertaken in the central Namib which has contributed to the problem identified in the study. Chapter 3 provides an overview of the geomorphological, geological and climatological history of the study area. Chapter 4 outlines the methods used in the study. Chapter 5 presents the base data and results of the study. Chapter 6 constitutes the discussion based on earlier chapters as well as a fairly extensive discussion of the dating problem associated with the Tsondab Sandstone Formation. Chapter 7 outlines the major conclusions reached in the study.

My interest in the geomorphology of the Namib desert was aroused whilst acting as a field assistant in a project organised by Professor P.D. Tyson and Dr. J.A. Lindesay, of the Climatology Research Group - University of the Witwatersrand, Johannesburg, to study the boundary layer wind systems over the Namib desert. The scope of the study was established in conjunction with Dr. M.J. Wilkinson of Lockheed Engineering (NASA) (formerly of the University of the Witwatersrand); his stimulating discussion at its inception is gratefully acknowledged. Dr. J.D. Ward of Cape Exploration (formerly of the Geological Survey, Windhoek) gave of his time in the field and has commented on preliminary drafts of this dissertation, which help is also gratefully acknowledged. Professor T.C. Partridge assumed supervision of the study on the departure of

Dr. M.J. Wilkinson, and has also reviewed the original drafts. Mr. T. Boyle of the Satellite Application Centre (CSIR) at Hartebeeshoek helped with the remote sensing work. The assistance of Dr. M.K. Seely and the D.E.R.U.N. staff is much appreciated, while the co-operation of the Department of Nature Conservation and Tourism of Namibia for permission to work in the Namib-Naukluft Park and for provision of accommodation at Gobabeb and Sesriem is acknowledged with thanks. I also wish to thank Mrs. W. Job for her skill and patience in drawing up the final diagrams.

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CHAPTER 1

INTRODUCTION

The central Namib desert has drawn many researchers over the last few decades in the fields of climatology, geography, geomorphology, geology, biology and zoology. Geomorphological research in the Namib desert has been undertaken by numerous authors. Two studies have come to differing conclusions as to the surface form of the Tsondab Sandstone Formation, an extensive deposit of supposedly early Tertiary to mid Miocene age. The spatial context, problems, objectives and area for this study are considered below.

Spatial Context

The Namib is one of five west coastal deserts lying within subtropical latitudes (Meigs, 1966). The Namibian component of the Namib desert stretches for 1360 kilometres of a total of 2000 kilometres along the coastal tract between the Olifants River in the Cape Province of South Africa and the Carunjamba River in southern Angola. The Namib varies in width from 50 to 150 kilometres and its eastern boundary, although not always clearly defined, generally corresponds with the 1000 metre contour. The piedmont plain is mantled by aeolian, marine, fluviatile and pedogenic deposits. The Namib is bounded to the west by the Atlantic Ocean and to the east ostensibly by the Great Escarpment. The central Namib desert is characterised at present by the dynamic sand sea of the Sossus Sand Formation, which covers most of the underlying Tsondab Sandstone Formation. The Sossus Sand Formation and underlying sandstone are crossed by four main linear oases, these being the Koichab, Tsauchab, Tsondab and Kuiseb Rivers; the latter is the only exorheic river and forms the northern boundary of the main Sossus Sand Sea.

The Problem

The Tsondab Sandstone Formation, which is an important feature of most the central Namib, has its origin in dune and sand sheet deposits of a palaeo desert (Besler and Marker, 1979; Martin, 1950, 1957; Ollier, 1977; SACS 1980; Selby, 1976; Ward *et al.*, 1983; Ward 1984a, 1987). Ward (1984a, 1987) has, however, recognised six facies of the Tsondab Sandstone Formation in the central Namib along the Kuiseb River, and has postulated a more complex depositional history. Besler (1980) envisaged the occurrence of a fluvial phase toward the end of the deposition of the Tsondab Sandstone Formation; this has been interpreted as an agent of modification acting upon the upper eastern facies of the Tsondab Sandstone, the eroded products of which were then re-deposited in the western areas. Besler (1980) also called the Tsondab Sandstone Formation the 'early Namib' dune field or the 'Namib Sandstone' and Besler and Marker (1979, 159) have classified it as "a typical red desert formation" a term adopted by SACS (1980) and Ward *et al.* (1983), whilst Marker (1977a, 1977b) used the term *Sandrock* to refer to these deposits. The problem of the origin and morphology of the Tsondab Sandstone Formation has previously been approached from different viewpoints: one with a geological emphasis (Ward 1984a, 1987) the other with a geomorphological bias (Besler 1980, 1984), these being expanded by various additional local studies and overviews.

The Axial Deposition Model

Ward (1984a, 1984b, 1987, 1988a, 1988b; Ward *et al.*, 1983) has studied the geology of the Kuiseb River area and has made a notable contribution to the understanding of the Tsondab Sandstone Formation. He has proposed a model in which the Tsondab Sandstone was developed, through time, by synchronous fluvial and aeolian sedimentation. This model provides for a system of dunes and sand sheets crossed by fluvial axes along which sediments are deposited. In the middle Kuiseb valley Ward (1984a) has defined and mapped six facies of the Tsondab Sandstone Formation. These comprise two rudaceous, three arenaceous and one carbonate unit (Fig. 1.1).

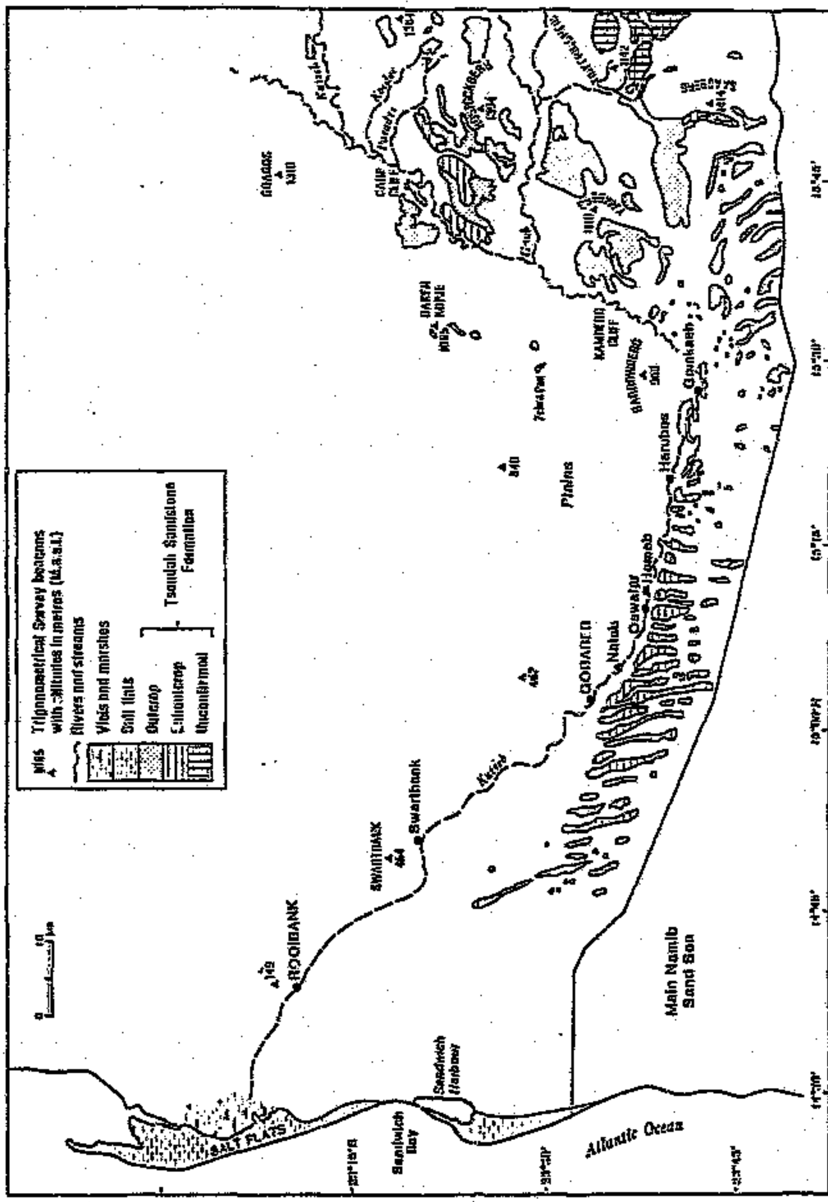

Figure 1.1: Map of the distribution of the Tsondab Sandstone Formation in the Kuiseb area (after Ward, 1984a).

The Low-Angle Fan Model

The Low-Angle Fan Model appears significantly different to the Axial Deposition Model for the later phases of the evolution of the Tsondab Sandstone Formation, in that it proposes a zone of proximal erosion near the Escarpment, with a zone of distal deposition nearer the coast (Fig. 1.2). Besler (1980, 1984) and Besler and Marker (1979) have viewed the Tsondab Sandstone Formation as arising from separate, diachronous phases of evolution. An earlier phase of aeolian deposition was followed by a phase of widespread fluvial modification. This fluvial remodelling has led to erosional truncation of the proximal deposits nearer the Escarpment and aggradation in the distal coastal areas (Besler, 1980, 1984). The fluvial modification is expressed as large, low-angle 'alluvial fans' which Besler (1980) identifies from gradient studies of the Tsondab Planation Surface (Besler, 1980) (Fig. 1.3). These features are, however, of extremely low-angle and are much larger than alluvial fans as generally understood (Bull, 1977; Cooke and Warren, 1973; Fryberger *et al.*, 1979; Mabbutt, 1977). Some southern African alluvial fans, however, are known to express this kind of relief, for example the Knersvlakte, which covers some 2500 km ^{2} (Partridge, 1990, pers. comm.). The Tsondab Planation Surface could easily represent a period where the rivers did not have the capability to reach the ocean, but yet had sufficient energy to remodel the Tsondab Sandstone Formation deposits. It is therefore suggested that these low-angled water-worked surfaces are synonymous with Ollier's (1977) 'pediments'. Distally these large pediments have given rise to the three to five wedges of colluvial sediment (Fig. 1.2) which are identified in the near-coast sedimentary record according to Besler (1980, 1984).

Other Work

Ollier (1977) found that cross-bedding within the Tsondab Sandstone Formation is consistent with dune sand deposition. He points out, however, that there are "possible foreset beds of a delta deposit ... (and) also plane-bedded sandstones" (Ollier, 1977: 208). He identified the presence of "...the Tsondab Planation Surface, a vast pediment crossed by east-west drainage..." (Ollier, 1977: 207), and saw the planation as truncating the aeolian deposits from the Escarpment

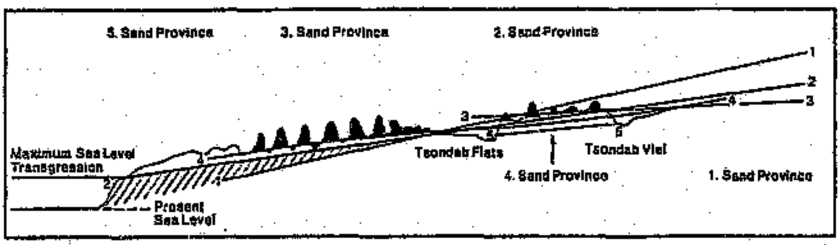

Figure 1.2: Five surfaces of truncation and aggradation (after Besler, 1980, 1984).

westward to the sea (Ollier, 1977), suggesting that sediment has been removed from the area of the present sand sea. Selby (1976) supported the idea of planation of aeolian sand sheet deposits (Fig. 1.4). His interpretation appears to assume the presence of fluvial forces large enough to truncate deposits of the Formation at its upper boundary. Lancaster (1984a, 1984b, 1984c) has identified features which are interpreted as reflecting depositional environments of semi-arid and extremely arid natures. "Dominant depositional environments have been sand seas and dune fields, with proximal and distal alluvial fan, ephemeral flood plain and pan or playa facies" (Lancaster, 1984c: 440). The flat surface morphology of the Formation is recognised by Lancaster (1984a, 1984c) but little explanation of its origin is offered.

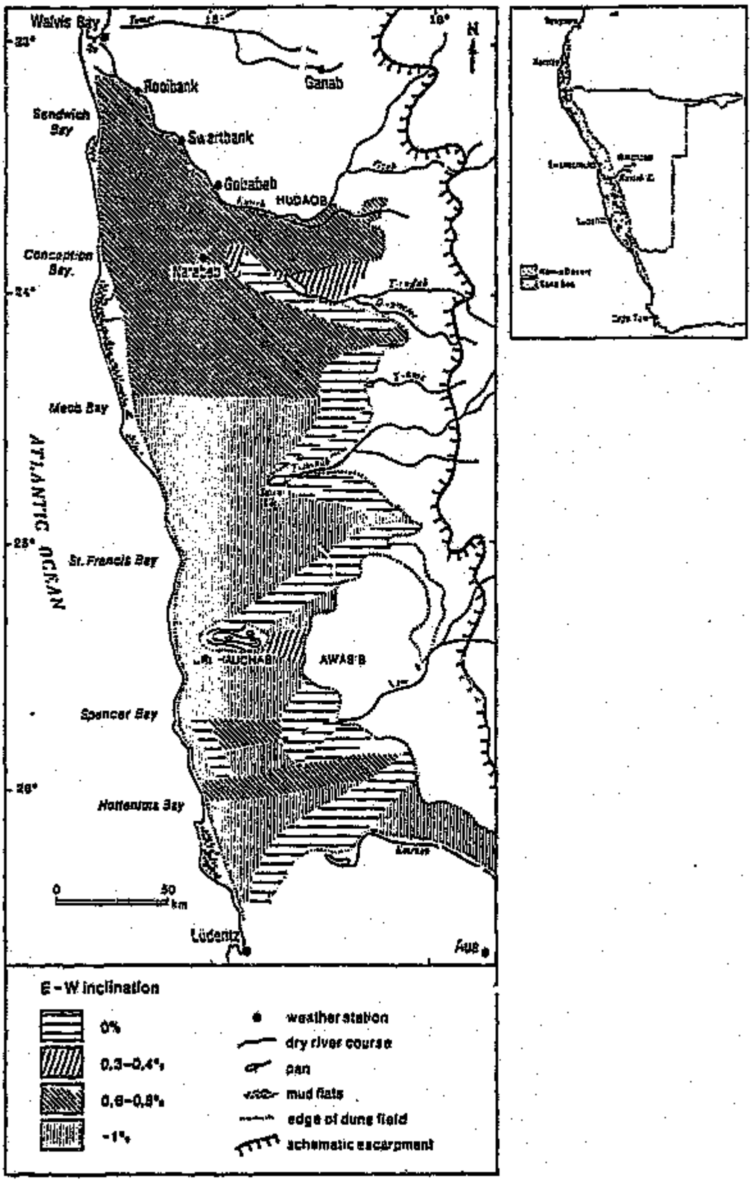

Figure 1.3: Tsondab Planation Surface gradients (modified after Besler, 1984).

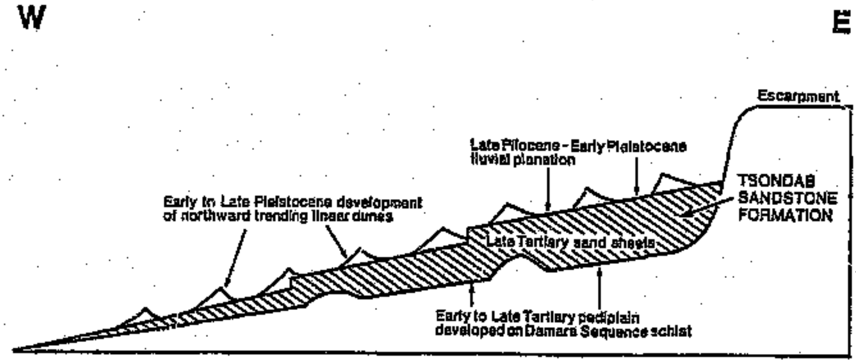

Figure 1.4: Development of the Tsondab Planation Surface (after Selby, 1976).

Objectives

Although numerous workers have contributed toward a geomorphological understanding of the deposits comprising the Namib desert, Ollier (1977) has pointed out that a spatially continuous geomorphic picture is absent. Ollier (1977), although providing a basic framework, also pointed out the lack of a geological history of the Namib; this has now been provided, in the Kuiseb River area, by Ward (1984a, 1987), and extended southward to encompass the Tsondab and Tsauchab valleys in the present study. Terrestrial sedimentary deposits of Tertiary age are not widespread in southern Africa (Partridge, 1985a, 1985b); therefore if a Tertiary age can be accepted for the deposits of the Tsondab Sandstone Formation, as has been argued, then these deposits, along with those of the Kalahari basin, are important not only locally, but in the context of the geological history of the entire subcontinent.

The chief differences in the viewpoints of Besler (1980, 1984) and Ward (1984a, 1987) concern the upper parts of the stratigraphic column of the Tsondab Sandstone Formation. Besler's model envisages 'alluvial' wedges (Besler, 1980, 1984) building on the west (distal) part of the Formation (Fig. 1.3). These 'alluvial' wedges extend over large areas and are responsible for the flat appearance of the Tsondab Planation Surface (Besler, 1980, 1984) (Fig. 1.3). Ward (1984a) sees a hiatus in axial deposition, followed by the emplacement of rudaceous deposits identified as the Karpfenkliff Conglomerate in the form of classic proximal alluvial fans. This, in turn, was followed by a phase of widespread calcrete pedogenesis of the Kamberg Formation, the combination of this rudaceous phase along with the pedogenic phase giving rise to the flat Tsondab Surface. The inherent difference between these two viewpoints is addressed in this study.

Lithofacies are discussed by the various authors, notably by Ward (1984a), who has described six facies in detail and has mapped them along the Kuiseb Valley. The field mapping of these facies in other areas to the east and south and an analysis of their spatial relationships has been used to make a contribution to the resolution of some of these differences.

Besler's (1980) accounts of distal (near-coast) parts of the Tsondab Sandstone Formation are detailed concerning surface deposits but limited in respect of the lower members. Ward (1984a) has published no data on the distal parts of the area. The work of Ward (1984a) is concentrated on a section where the deposit tends to thin out over the Damara schists (Besler, 1980, 1984). How Ward's (1984a, 1987, 1988a) model relates to more southerly and easterly exposures is shown in the present study.

Study Area

The fieldwork area for this study was restricted to an area between the Walvis Bay-Rössing road, and 25° south latitude, which is bounded to the west by the Atlantic Ocean and to the east by the Great Escarpment (Fig. 1.5). Within this area several key areas were recognised:

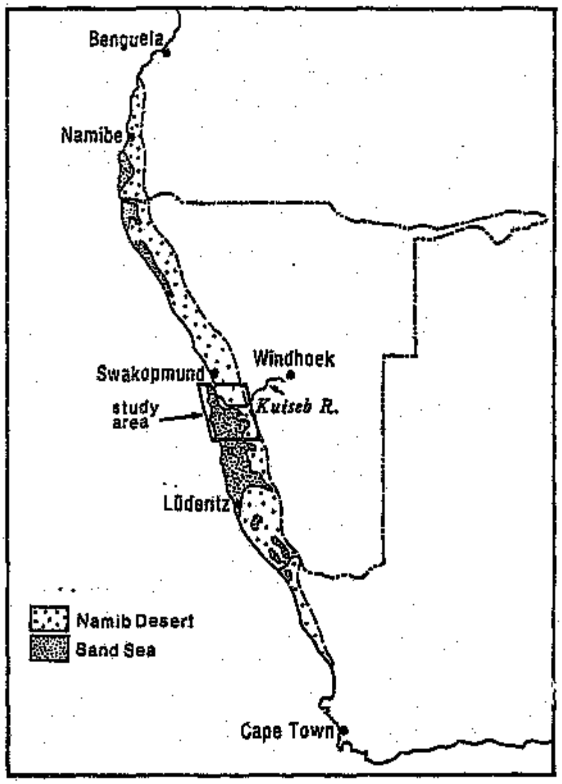

Figure 1.5: Namibia showing the central Namib desert and the study area for this investigation.

1. The interfluve between the Kuiseb and Gaub Rivers,

2. The upper Kuiseb River,

3. The Tsondab River and parts of its interfluve with the Gaub and Kuiseb Rivers,

4. The Tsauchab River and parts of its interfluve with the Tsondab River,

5. Near coastal areas south of Rooibank,

6. Interdune valleys between Gobabeb and Natab,

7. Exposures on either bank of the middle and lower Kuiseb River,

8. Interdune valleys south of Swartbank, and

9. Parts of the stony desert to the north of the Kuiseb River.

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Chapter 1 has set the spatial context for the study, including a brief review of the problem and objectives of the current research as well as setting out the study area used. A review of the previous work undertaken in the central Namib, contributing to the problem identified in this study, is put forward in Chapter 2.

CHAPTER 2

PREVIOUS WORK

Two main models for the formation of the Tsondab Sandstone have been proposed as outlined in Chapter 1. These are the Axial Deposition Model and the Low-Angle Fan Model. These are summarised below.

The Axial Deposition Model

Ward (1984a, 1987) has proposed a chronology and formal nomenclature for what he has called the Proto-Namib Palaeo Desert Phase, Karpfenkliff Fluvial Phase, and Pedogenic Phase, which embraced the deposition of the Tsondab Sandstone proper, subsequent conglomerate capping and calcrete formation. A main aim of his study was to investigate the role of the Kuiseb River and its relationship to the Palaeo Desert and main Namib sand sea (Sossus Sand Formation) (Ward, 1987).

Ward (1984a, 1987) recognised six predominant facies which he classified as being part of the Tsondab Sandstone Formation, as well as overlying conglomerate formation and a calcrete formation. These are described as follows. On the floor formed by the Namib Unconformity Surface there is a quartz breccia referred to by Ollier (1977) as Basal Conglomerate, which grades into the quartzose sandstones. This Basal Breccia is thin, being only about 3 metres at its thickest reported occurrence. This deposit has been formally given member status and is referred to as Gomkaeb Basal Breccia (Ward's (1984a, 1987) Facies A). The type locality for the Gomkaeb Basal Breccia Member is at Gomkaeb corner (23°42,5'S; 15°29'E) about sixty kilometres upstream of Gobabeb. The breccia is not necessarily spatially continuous, and the overlying quartz arenites rest directly on the Namib Unconformity Surface at places.

Ward (1984a, 1987) pointed out that the Basal Breccia Member grades upwards into a locally restricted rudaceous facies (Facies B) or a quartz arenite facies (Facies E). Ward's (1984a, 1987) Facies B comprises a 10 metre thick deposit. The type area for this deposit is located at Gomkaeb corner the point where the Kuiseb changes its course from south-westerly to west-north-westerly.

Ward has referred to his Facies C and D as "typical Tsondab Sandstone" (Ward, 1987, 12). These are the facies which generally comprise the reddish brown, massive deposits, with common dune cross bedding. The deposits of Facies C are consolidated, with only some cementation having been noted, whereas Facies D is generally carbonate cemented. Several authors (Besler, 1979; Ward, 1987; Watson, 1980) have noted patchy gypsum occurrences within the matrix forming small lenses. Cross stratification is evident, with foresets dipping to the west-north-west to east-south-east (Barnard, 1973; Besler and Marker, 1979; Ward, 1987). Fossil termitaria are also a common component of this deposit, being well delimited by preferential areas of calcium carbonate precipitation.

Facies D sandstones exhibit geometrical features referred to as patterned ground in the literature, and previously recognised by Besler (1972a), Goudie (1972), Ollier and Seely (1977), Watson (1980) and Ward (1984a, 1987). Ward (1987) has related these to the 30-150m wide and up to several kilometre long (Fig. 2.1) macrofractures common in this desert. Facies D shows a close relationship to the distal gravel lag deposits of the Karpfenkliff Conglomerate Formation.

Facies E consists of quartz arenites which are carbonate cemented (calcite and dolomite). The facies contains angular to sub-rounded quartz sands with localised concentrations of garnet and mica. This facies consists mainly of fluvially derived or reworked sediments, at times interdigitating with aeolian elements. These deposits are located in the proto-Kuiseb bedrock depression and should effectively be divided into a true Facies E and a marginal boundary facies. Those facies that are fluvial in origin contain scatters of pebbles which become less pronounced westward.

Facies F contains few or no arenites. The facies has been named the Zebra Pan Carbonate Member and is associated with Facies C and E either as capping

Figure 2.1: Macrofractures (arrowed) in the Tsondab Sandstone south of the Kuiseb River, near Gobabeb

or interbedded with them. This member is also found lying directly on the Precambrian schists north of the Kuiseb. The composition of the carbonates is mostly dolomite, although some calcium carbonate has been recorded.

The Low-Angle Fan Model

Besler (1980) has invoked a standard model of desert landform development in which two main surfaces are recognised: the erosional surface of the pediplain which grades laterally into a bahada, or surface of deposition (Walton, 1969). Besler (1984), although pointing out that her work was preliminary, recognised two main processes that have acted on the consolidated fossil surficial deposits comprising the Tsondab Sandstone Formation. Firstly a phase of fluvial activity gave rise to what she has interpreted as the Post-African Planation Surface; this upper surface is known as the Tsondab Planation Surface and is higher in elevation than the Namib Unconformity Surface which she considers to be the African. Secondly, decreasing runoff was interpreted as favouring the emplacement of large alluvial fans.

Besler (1984) based her conclusions on analysis of 1:100 000 and 1:250 000 contour maps issued by the South African Government Printer, together with a fieldwork exercise. Analysis of 38 latitudinal cross-sections led to the compilation of a spatial one-dimensional surface gradient model for the Namib Desert (Fig. 1.5); this shows the Tsondab Planation surface to have a gradient of 0% to 1%, similar to King's (1962) Post African denudational land surface. Besler (1984) has interpreted only the slightly consolidated aeolian arenaceous deposits as Tsondab Sandstone Formation.

Besler (1980) viewed the Tsondab Planation Surface as the product of unconfined fluvial processes and has suggested that eroded sandstone from the proximal (near Escarpment) facies of the Tsondab Sandstone Formation, in the form of *Randfurche*, was redeposited over true Tsondab Sandstone in the distal areas to the west. These deposits are thought by Besler (1984) to have been deposited as large alluvial fans as decreasing fluvial discharge in the area changed the fluvial regimes from exorheic to endorheic and the flow reach of the various rivers retreated inland. Much of the support for this conclusion is derived from granulometric and morphoscopic studies of dune sands of the Sossus Sand Formation. Differences in the properties o these sands were used also in estimating the sizes of the fans, and led to the conclusion that the fans decreased in size from north to south.

Besler's (1980) main focus was along the so-called northern erg (Fig. 1.3). Here the upper planation surface, with a gradient of 1%, is cut across the consolidated sandstone. A second surface is considered to be superimposed on this surface. This second surface has a gradient of 0.6 to 0.8% and represents a truncation in the east and large aggradation in the west (Fig. 1.2). These two phases represent the major surficial events affecting the Tsondab Sandstone Formation according to Besler (1984). Incised below these two surfaces are a further three postulated incisions mainly represented by terracing within rivers such as the Kuiseb, Gaub and Tsondab. Besler (1980) has also postulated that the Tsondab Flats represent a more recent alluvial plain associated with erosional stage 4 (Fig. 1.2). Besler (1984) has also suggested that the Tsondab Sandstone Formation forms the major source for the sands of the Sossus Sand Formation, interpreting a trend of increasing patina and sorting eastward to reflect fluvial transport from the east rather than aeolian transport from the west.

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Chapter 2 comprised a review of previous work undertaken in the Central Namib. Chapter 3 sets out the geomorphological, geological and climatological background for this work.

CHAPTER 3

OVERVIEW OF THE GEOMORPHOLOGICAL, GEOLOGICAL AND CLIMATOLOGICAL HISTORY OF THE CENTRAL NAMIB TRACT

The geological and climatic history of a region is of great importance to any geomorphological investigation. An overview of the historical development of the Namib tract in these areas is given below.

General Climatic History

Before anthropogenic influences became a critical forcing mechanism, climatic and geologic changes were the main factors in geomorphological change. Although large scale geological changes have occurred through plate tectonics, geomorphological responses have been mainly a result of changing climatic regimes. Geological changes wrought by uplift and tilting have, however, had their own geomorphological effects which will be discussed separately.

Climatic events of the last 150 million years affecting the subcontinent.

One of the most notable influences on the climate of southern Africa arose from the fragmentation of Gondwanaland, which was then about 14° further south than at present (Smith and Briden, 1982), and the creation of oceans surrounding the sub-continent on three sides. Thus the almost ubiquitously tropical Mesozoic, associated with a circumglobal equatorial ocean with a relatively uniform thermal structure and lack of important latitudinal temperature gradients (Tyson, 1986), was replaced by cold oceans with strong latitudinal temperature gradients. These changes tended to occur in steps rather than as a smooth transition during the Cainozoic (Miller and Fairbanks, 1985), the most important features being changes in geometry and inter-connection between ocean basins and cryoformation around continental Antarctica (Tyson, 1986). During the very late Palaeocene to early Eocene sea surface temperatures in the high southern latitudes were of the order of 20°C (Shakleton and Kennett, 1975).

The warm Cretaceous climates experienced a sudden change at the Cretaceous-Tertiary (K-T) boundary (about 65 Ma). This change was accompanied by mass extinction and is thought to have originated through either the impact of extraterrestrial bodies with the earth (Hut *et al.*, 1987), or volcanism and epeirogenesis (Hallam, 1987).

Shackleton and Kennett (1975) have shown that a major decrease in southern African ocean temperatures (~5°C) occurred at about 38 Ma. This is seen as a possible response to the first occurrence of ice in the Antarctic, followed by cooling at about 30 Ma. The main Antarctic ice cap was formed by 14 Ma and was followed by further cooling at 10 Ma, at 5,5 Ma (Messinian) and again at about 2,4 Ma with the formation of the Arctic polar ice cap; a final major cooling surge occurred at 0,9 Ma. All of these cooling episodes were associated with sea level drops of the order of 30 to 50 metres (Miller and Fairbanks, 1985). Epeirogenic uplift was associated with two of these events; at 18 Ma uplift of 150 to 300 metres took place, and just prior to the 2.4 Ma cooling, upwarping of 600 to 900 metres occurred (Partridge and Maud, 1987). It has been suggested that Tertiary volcanism could have triggered other cooling events (Kennett and Thunnell, 1975; Vogt, 1972). Warming and deglaciation occurred in the early and mid Pliocene (Harwood, 1985; Webb *et al.*, 1984) resulting in the formation of marine terraces between 60 and 110 metres along the sub-continental coast (Partridge, 1990).

The cooling event at 2,4 Ma mentioned earlier brought the Pliocene warming events to an end and led to the re-establishment of the east Antarctic ice sheet (Denton, 1985; Harwood, 1985). Climatic deterioration evident in the southern African terrestrial deposits at this time is associated with the appearance of later species of Australopithecines and *Homo habilis*, and intensification of Milankovitch cycles as evidenced by marine isotope records (Partridge, 1990), leading to the Quaternary glacial cycles.

Aridity in the Namib Tract: its Causes and Possible Age

Two main causes of aridity along the south western coast of Africa have been postulated. First there is the effect of the Benguela Current and its associated cold upwelling waters (Siesser, 1978; Van Zinderen Bakker, 1975). Secondly, there is the location of the anticyclonic system over the South Atlantic which has a drying effect through the semi-continuous presence of subsiding air (Tyson, 1986). Summer rainfall is limited due to the influence of the South Indian (ocean) Anticyclone whose moisture bearing winds are drained as they cross the continent from east to west, or are trapped by the temperature inversion at the eastern Escarpment. Scholz (1972) also attributed aridity in the Namib Desert directly to the cooling effect of the Benguela Current on westerly winds, thereby reducing their capacity for carrying water vapour.

The Namib Desert is located on a relatively narrow bedrock pediplain (having a regional 1° bedrock surface slope towards the Atlantic). This pediplain has its origins in either the erosional retreat of the Great Escarpment, and the grading of the coastal tract to a new base level after the breakup of West Gondwana during the late Mesozoic (Martin 1975), or in the re-planation of the deeply kaolinized African Surface to a new Post African 1 level (T.C. Partridge, pers. comm., 1989). The Atlantic Ocean, according to palaeomagnetic, radiomagnetic, and palaeontological studies, opened about 127 Ma (Simpson, 1977; Tankard *et al.*, 1982). Fully marine conditions were established by about 80 Ma.

Between the Kuiseb River and the Lüderitz-Aus area deposits (the Tsondab Sandstone Formation) of supposedly Tertiary age (Besler 1980; SACS 1980; Ward, 1984a, 1987) correlate quite markedly with the boundaries of the overlying Sossus Sand Formation (Barnard, 1973; Besler 1976, 1977, 1980; Besler *et al.*, 1977; Besler and Marker, 1979; Martin, 1950; Ollier, 1977; SACS 1980; Selby, 1977); this contrasts with the situation further north (Wilkinson, 1987, 1988a, 1988b; Ward, 1989, pers. comm.). Significant erosional features of the pediplain are the numerous inselbergs which remain dotted across the land surface. This pediplain is generally referred to as the Namib Unconformity Surface, a term coined by Ollier (1977, 1978). The Namib Unconformity Surface forms a fundamental datum in any study of the depositional history of the central Namib

(Ollier, 1977), forming a spatially important marker for the beginning of the deposition of the Tsondab Sandstone Formation. As such the dating of this surface is of great importance. Some workers have postulated formation (or exhumation) to have occurred during the late Cretaceous (Martin, 1973, 1975; Ollier, 1977, 1978; Seely and Ward,1988; Ward, *et al.*, 1983). Others have suggested a Miocene age based on theories linking the Namib aridity to the inception of the Benguela Current during the late Miocene and the absence of any remnants of the African surface (formed during Cretaceous and earliest Tertiary times) in this area (Partridge, pers comm., 1989; Siesser, 1978, 1980; van Zinderen Bakker, 1975, 1984).

General Geomorphological and Geologic History

Aridity in the Namib has led to the accumulation of a thick deposit of arenites, both active and fossilised, within the central Namib. The form of this arenite and the possible sources need to be outlined.

Arenites

Many workers have reported the presence of reddish-brown arenites underlying the Sossus Sand Formation (*inter alia* Barnard, 1973, 1975; Besler, 1976, 1977, 1980; Gevers 1936; Goudie, 1972; Harmse, 1980; Logan 1960a, 1960b; Marker, 1977a, 1982; Marker and Müller 1978; Martin, 1950, 1957; McKee 1982; Ollier 1977, 1978; Rust and Wieneke, 1974, 1980; Stapff 1887; Selby, 1976, 1977; Vogel 1982; Ward, 1982, 1984a, 1984b, 1987; Wilmer 1893). These arenites have been accorded various names in the past, but Ollier (1977, 1978) referred to them as the Tsondab Sandstone after the massive cliff exposures at Tsondab Vlei. Besler and Marker (1979) referred to them as the Namib Sandstone owing to their wide distribution within the desert zone. The South African Committee for Stratigraphy (SACS, 1980) has formally designated the arenites as the Tsondab Sandstone Formation, the type locality being the 60 to 90 metre high sandstone cliffs on the north eastern side of Tsondab Vlei.

The arenaceous quartzose material comprising the Tsondab Sandstone Formation is everywhere cemented to varying degrees (Besler and Marker, 1979; Ollier, 1977; SACS, 1980; Ward, 1984a, 1987). Its occurrence is practically continuous in the area between Lüderitz and the Kuiseb River (Besler and Marker, 1979; Martin, 1950, 1973; SACS, 1980). Outcrops further north have been observed, however (Ward, 1987), and further tentative links have been made to other sandstone bodies to the north of the study area, for example the Tumas Sandstone (M.J. Wilkinson, 1988: pers. comm.), as well as sandstones underlying the dunes of the Skeleton Coast in northern Namibia and beyond the Kunene River in southern Angola where these sandstones underlie the Catrona Conglomerate (Soares-Carvalho, 1961, J.D. Ward, 1989: pers. comm.).

The Karpfenkliff Conglomerate Formation and the Kamberg Calcrete Formation cap the arenites of the Tsondab Sandstone Formation along palaeo-channels, whereas on the interfluves the capping is of Kamberg Calcrete only. Towards the coast the sandstone is bevelled, uncemented to lightly cemented, and in some places capped by lag gravels derived from weathering of the Karpfenkliff Conglomerate Formation.

Origins of the sands of the Namib tract

No major statements concerning the origin of the sands of the Tsondab Sandstone Formation have been made. Most contributions are aimed at defining the origins of the presently active sands of the Sossus Sand Formation. Two main hypotheses have been postulated for the source of the sediments of the Sossus Sand Formation. The first invokes deflation of the Tsondab Sandstone Formation (Besler, 1980; Besler and Marker, 1979). This contrasts with the theory of ongoing sediment accumulation suggested by Rogers (1977) and developed by Lancaster (1981), Ollier and Lancaster (1983) and Lancaster (1989).

Besler (1980) and Besler and Marker (1979) have suggested a largely fluvial origin for the sedimentary input. The aeolian facies of the Tsondab Sandstone Formation along the Great Escarpment are thought to have been fluvially eroded during the Last Glacial Period and redeposited as a series of alluvial fans to the west. These were then partly reworked by southerly winds into the dunes of the Sossus Sand Formation. This scenario is strongly reminiscent of hypotheses of sand sea formation in the Sahara (Alimen *et al.*, 1958; Capot Rey, 1970).

Lancaster (1982) views the Sossus Sand Formation as an ongoing accumulation. High energy southerly winds in the southern Namib have been shown to have a massive potential for the movement of beach sands into the main sand sea. These southern beaches are supplied with sediments through longshore movement northward from the Orange River mouth. The modern dune sands were closer to sands of the inner shelf and beaches of the Atlantic than the sands of the Tsondab Sandstone Formation, which through association with abundant clinopyroxene particles in these sands (Lancaster and Ollier, 1983) are thought to have been derived from rocks of the Namaqualand Metamorphic Complex via the Orange River.

When considering the volume of sand comprising the Tsondab Sandstone Formation, it seems most likely that the beaches and adjoining areas of the continental shelf exposed during limited glacio-eustatic regressions and possibly tectonic movement, along with fluvial input from the Escarpment and highland zone, provided the sources for these massive deposits.

The Benguela System

The Benguela Current is one of four major eastern boundary region currents of the world (Shannon, 1985). As is the case with the other three (the California, Canary and Peru currents), it is characterised by a persistent upwelling system involving the upsurge of cold bottom waters and equatorward flow (McLain *et al.*, 1985). The Benguela System is unusual in that it is bounded to both north and south by areas of relatively warmer water (Siegfried, 1989). The onset of the Benguela System was originally assigned to the Cretaceous by Kaiser (1926). Van Zinderen Bakker (1975), who supported the notion that the Benguela Current was the major initiator of arid conditions in the area, initially proposed an early Oligocene age for the onset of arid conditions in the Namib based on Shackleton and Kennett's (1975) 38 Ma age. Other workers concluded that the Benguela

System had its onset during the Plio-Pleistocene (Endrödy-Younga, 1978; Tankard and Rogers, 1978; Seely, 1978).

Deep sea drilling on the Walvis Ridge Abutment has recovered a long sequence of sediments dating from the middle Eocene to the late Pleistocene Using various biotic characteristics of the constituent diatom, plankton and nannoplankton faunas, Siesser (1978) has been able to reconstruct changes in the characteristics of the ocean water including the onset and nature of the Benguela Current. The major conclusion derived from sedimentological, palaeontological and geochemical data from the region was that a "weak spasmodic introduction of cool, upwelled waters *(occurred)* along this coast from middle or late Oligocene until middle Miocene times. In the early late Miocene conditions changed markedly, strongly suggesting intensification of upwelling which brought cold, nutrient rich waters to the surface along the coast." (Siesser, 1978: 105).

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Chapter 3 has provided an overview of the geomorphological, geological and climatological history of the area. Within the framework outlined, a set of methods was established as outlined in Chapter 4.

CHAPTER 4

METHODS

Fieldwork was undertaken in the area during two trips between September 1988 and April 1989. This work was supplemented by examination of aerial photography (Job 774 of 1977, scale 1:50 000) as well as survey maps, satellite imagery (Figs 4.1 & 4.2), and image processing. The Tsondab Sandstone was studied chiefly in outcrop form. Outcrop sections were measured manually with a tape. Some sections are identical to those measured by Ward (1984a, 1987) and tape measurements generally agree with abney measurements. Much of the Tsondab Sandstone has been designated as suboutcrop, in conformity with the approach of Ward (1984a, 1987), because in many cases the arenites are capped by either the Karpfenkliff Conglomerate or the Kamberg Calcrete. Observations were also made outside these areas, although fieldwork was hampered by private property or restricted access.

Visual appraisal in measured sections of these often undifferentiated deposits was found to be the best way to determine facies relationships. The sedimentary succession of the Tsondab Sandstone Formation was generally studied by measuring the exposed succession in streambeds, on ridge crests, and in the open field. The deposits have been studied chiefly from within a uniformitarian (modern analogue) approach. Using field sketches and photographs with superimposed scales, two-dimensional sections have been constructed (Appendix 4) partially illustrating the main events in the deposition and subsequent alteration of the Tsondab Sandstone Formation. Deposits have been described according to thickness and geometry, contacts, rock type, and sedimentary structures. Graphic logs of key sections have also been used.

Although thicknesses of 40-200 metres have been assigned to the Tsondab Sandstone Formation at times (Besler and Marker, 1979), no sections of more than about 70 metres have been encountered thus far in the northernmost area. Seismic investigations of Van Zijl (1970) gave thicknesses of 40-60 metres for the bevelled sandstone south of Swartbank, whilst Ward (1984a, 1987) recorded

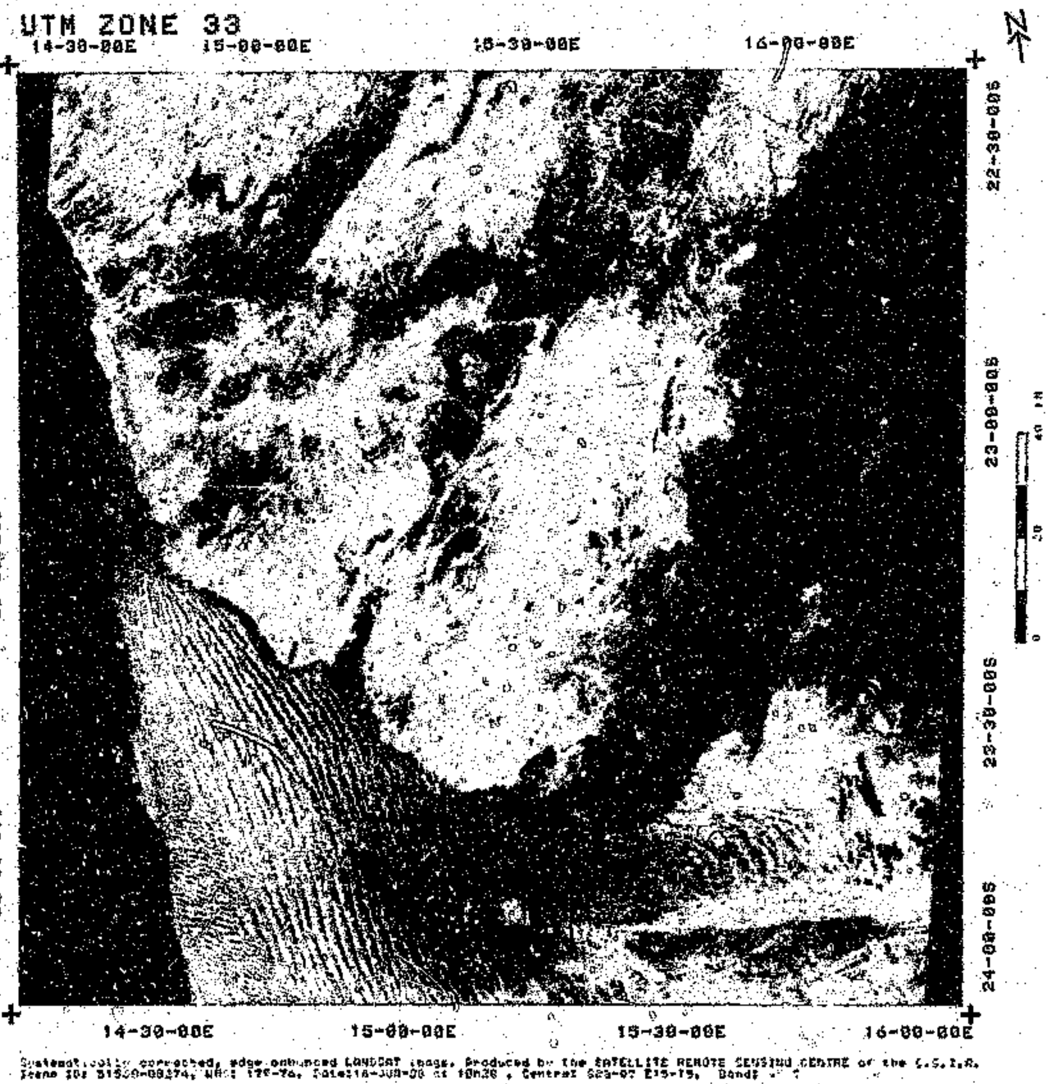

Figure 4.1: Satellite image of the Kuiseb River forming the northern boundary of the main Namib Sand Sea

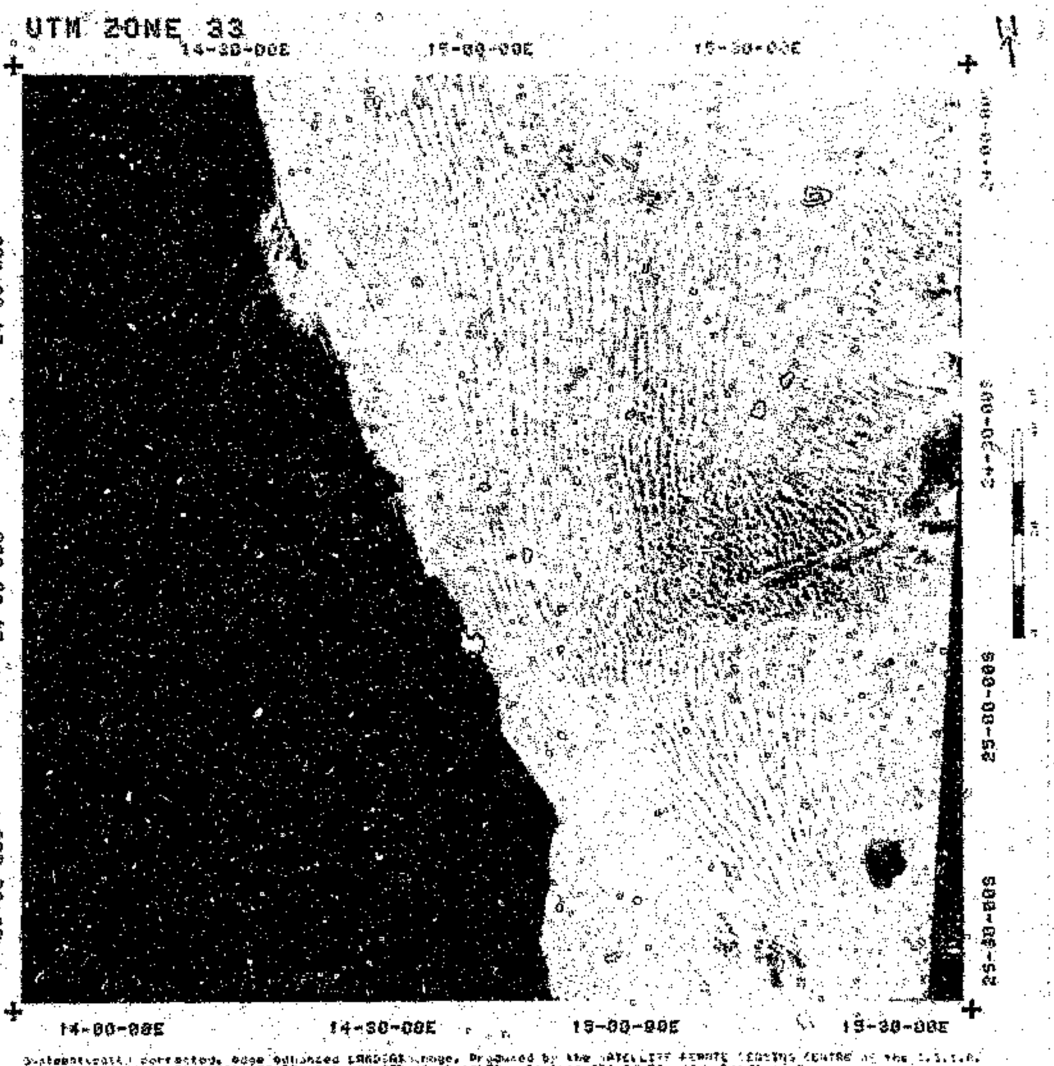

Figure 4.2: Satellite image of the area south of Tsondab Vlei in the central Namib desert.

maximum thicknesses of about 70 m. Barnard (1973) reported thicknesses of 220 metres at Dieprivier. Sections at Tsondab Vlei reach heights of up to 100 metres, but the basal contact with the Namib Unconformity Surface is concealed.

The apparently flat form of the Namib Unconformity Surface and the Tsondab Planation Surface turned out on investigation to be made up of gently sloping erosional or depositional (pan playa or fluvial axes facies) surfaces. The succession generally has a seven facies association. These reflect sedimentological controls associated with local environment changes as well as external controls such as tectonic movements, sea level oscillations and climatic changes. The Tsondab Fluvial phases are sub parallel while aeolian facies are parallel oblique to tangential oblique.

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The methods used in this study have been outlined in Chapter 4, following which, the base data and results of the study are presented Chapter 5.

CHAPTER 5

RESULTS

Facies already reported in the northern part of the study area were re-examined at their type localities in order to confirm published descriptions. These type sections are reproduced in the following descriptions along with spatially new exposures of each of the facies. A new facies and its type section is also described.

Field Data

The sedimentary succession within the Tsondab Sandstone Formation is reasonably clear. On the basement formed by the Namib Unconformity Surface rests the thin Gomkaeb Basal Breccia Member. This is capped either by coarse grained angular to sub-rounded deposits, interpreted variously as colluvial in origin, aeolian, or fluvial. These deposits grade upwards with either sharp or diffuse boundaries into conglomerates or calcretes. Interbedded within the above deposits are occasional dolomite-carbonate facies.

Gomkaeb Basal Breccia Member - Facies A (Fig. 5.1)

This member is relatively thin, reaching a maximum thickness of about 3 m. It consists mainly of quartz clasts derived from the Precambrian schist (Damara) bedrock material. These clasts are angular to subangular and are supported in a cemented matrix of quartz sands and mica flakes. The clasts are pebble to cobble size. There are numerous garnets within the matrix ranging up to pebble size. Although calcium carbonate is the cement, Ward (1987) reported the presence of minor amounts of dolomite. Stratification is absent within this member.

The quartz pebbles and cobbles and garnetiferous components are derived from the underlying Kuiseb Formation schists (Damara), as was observed by Ollier (1977). The metagraywackes and metapelites of the Kuiseb Formation are also present in the study area. The mineral constituents and depths of these deposits indicate palaeo regoliths or lithosols (Ward, 1987) developed on the Namib Unconformity Surface. Similar deposits are present on the Kuiseb

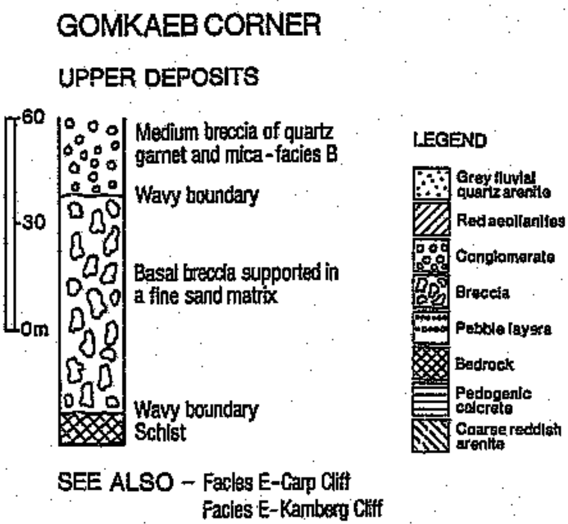


Figure 5.1: Graphic log of the Gomkaeb Basal Breccia.

Formation metasediments in the Khomas Hochland (Ward, 1984a, 1987). Suggested analogues for the Gomkaeb Basal Breccia are found in the southern Namib, the oldest Tertiary terrestrial sediments being those of the Chalcedon-Tafelberg Silcrete Formation which are probably dateable to the Palaeocene (SACS, 1980). It can, however, be argued that the Gomkaeb Basal Breccia is of Miocene age (Selby, 1976). Deposits of this basal breccia occasionally grade upwards into rare deposits of Facies B rudaceous sediments as well as the more extensive Facies E deposits.

Facies B (Fig. 5.2)

The type locality for these deposits, which are up to 10 m thick, is located at Gomkaeb corner (23°40' S; 15°26' E), where the Kuiseb changes direction from southwesterly flow to west-north-westerly. This deposit was recognised as being lithologically similar to the Gomkaeb Basal Breccia by Ward (1984a, 1987), and

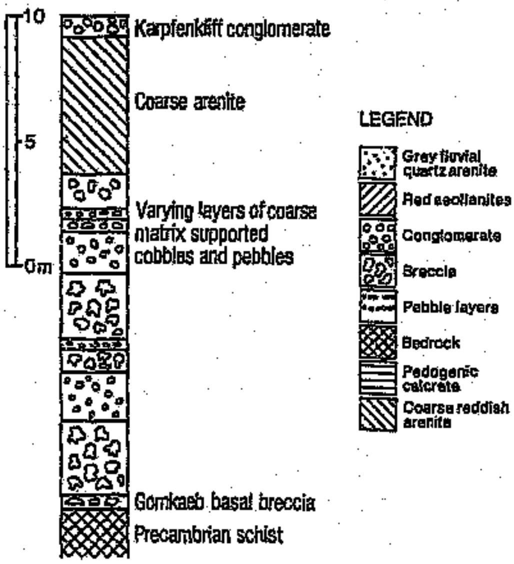


Figure 5.2: Graphic log of Facies B.

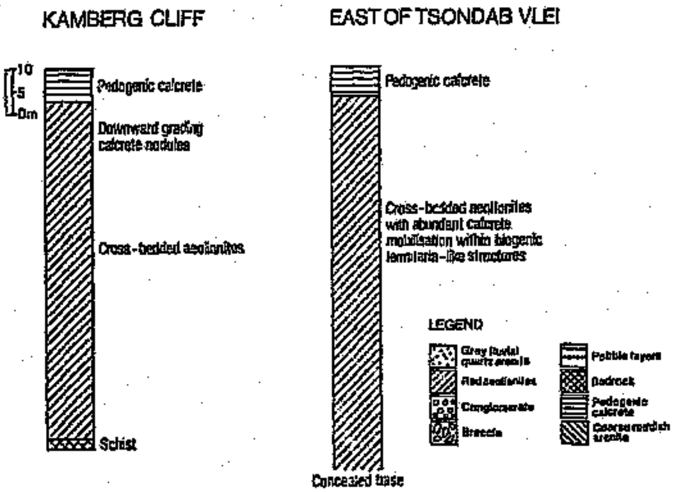


Figure 5.3: Graphic log of deposits of Facies C.

has been termed breccia conglomerate. It is comprised of smaller quartz pebbles which are angular to sub-rounded, and are associated with numerous small garnets. The coarse fraction is cemented and supported by a coarse grain matrix of quartz sand, garnet and some mica. Ward (1987) reports the cementing medium to be calcite and dolomite. Cross-stratification has been noted within these deposits, which are thought to be colluvial in origin because of the angularity of the constituent particles. They probably originated as colluvial wash from local topographic highs. Horizontal stratification of coarser pebbles and some clasts is common, with rare cross-stratification apparent in the deposits as a whole.

Facies C (Fig. 5.3)

These deposits are weakly consolidated along interfluves, becoming more strongly cemented towards fluvial axes; the deposits react weakly to acid, indicating other forms of cement along with calcium carbonate. These deposits tend to have a red brown (5YR) colour although they do in places tend toward deep red (2.5YR). Several factors point to the aeolian origin of these quartz arenites, including the actual composition and morphology of the quartz grains, the red ferric oxide patina on rounded to sub-angular grains, as well as the medium to large-scale tabular planar and wedge planar cross-bedding with predominant west-north-west to east-south-east azimuths; these suggest a prevailing southerly quadrant wind regime (Bigarella, 1972) similar to that prevailing at present. Other features of this facies are well developed biogenic components, including termitaria-like features and golden mole-like trails (*Eremitalpa* sp.). Selby (1976) interpreted these features as root casts and rhizomorphs formed by calcium carbonate remobilisation. Seely and Mitchell (1986), in a comparative study of the termitaria-like structures and associated tubules with the burrow system of *Hodotermes mossambicus* (Hagen) (harvester termite), came to the conclusion that, at least in part, the calcified tubules are fossilised remnants of termite burrows. The Arab term 'dikaka' is widely used to describe similar features in northern deserts whose origin remains enigmatic; plant root channels (Glennie and Evamy 1968), termite burrows and solution pipes are some suggestions. Acheulean Industry tools are often found lying on the surface of this deposit; these are, however, based upon material derived from the Karpfenkliff Conglomerate Formation.

The cross bedding exposed in this facies is commonly observed in modern dunes (Figs. 5.4 and 5.5). The cross beds generally dip in a north-easterly direction, confirming reports of Barnard (1973), Besler and Marker (1979) and Ward (1984a, 1987). Analogous internal structures in modern dunes led Ward *et al.* (1983) to suggest that palaeo wind regimes were similar to those of today with dominant southerly winds.

Facies D (Fig. 5.6)

These deposits tend to have a red brown colour (5YR) with bedding disrupted or not apparent. These deposits are also indicative of an aeolian origin, based on the composition and morphology of the subangular quartz grains and the red oxide patina. This deposit is diagenetically cemented and has developed large-scale macrofractures (30-150 m wide) and patterned ground features (including polygons of up to 20 m in diameter).

Facies E (Fig. 5.7)

These deposits are similar to those preserved in the current channels of the active rivers of the central Namib. At places they interdigitate with deposits of Facies C and possibly Facies D (Fig. 5.8). Lenses of gravels and pebbles are associated with these deposits, and mica and garnets are present. The main arenites are poorly to moderately sorted with sub-angular to sub-rounded quartz grains. The deposits mostly lack internal sedimentary structures besides being massively horizontally layered, an exception being the interdigitating facies. These sediments are mainly greyish to whitish (10YR) with occasional reddish brown lenses (5YR), and diagenic mottling is common (Fig. 5.9). The cliff exposures of these deposits are quite often coated by tufa (Fig. 5.10), which has, in places, been interpreted as vegetative casts (Martin, 1957; Selby, 1976); however, these features may also be mainly a diagenic product of calcium carbonate

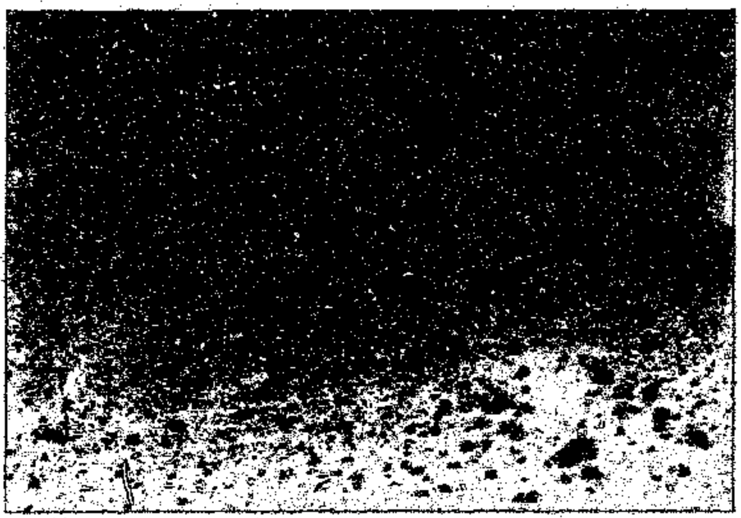


Figure 5.4: Cross bedding (arrowed) commonly observed in facies of the Tsondab Sandstone Formation.

Figure 5.5: Cross bedding (arrowed) found in linear dunes along the Kuiseb River in the Sossus Sand Formation.

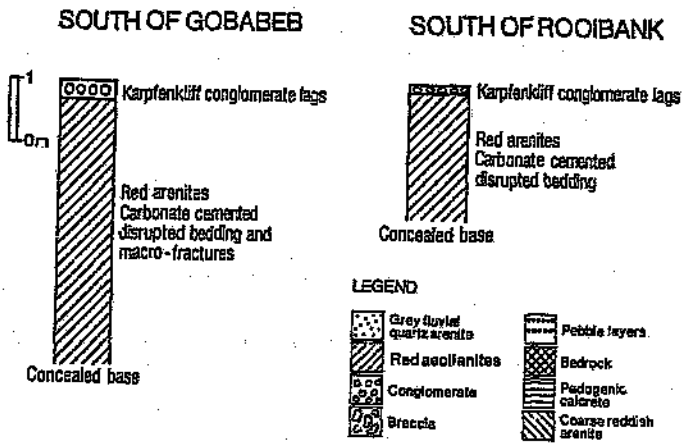


Figure 5.6: Graphic log of deposits of Facies D.

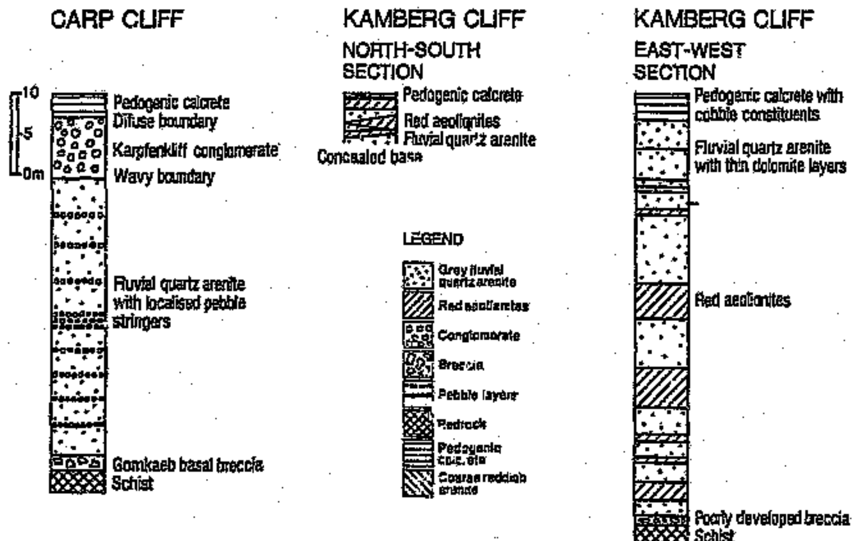


Figure 5.7: Graphic log of deposits of Facies E.

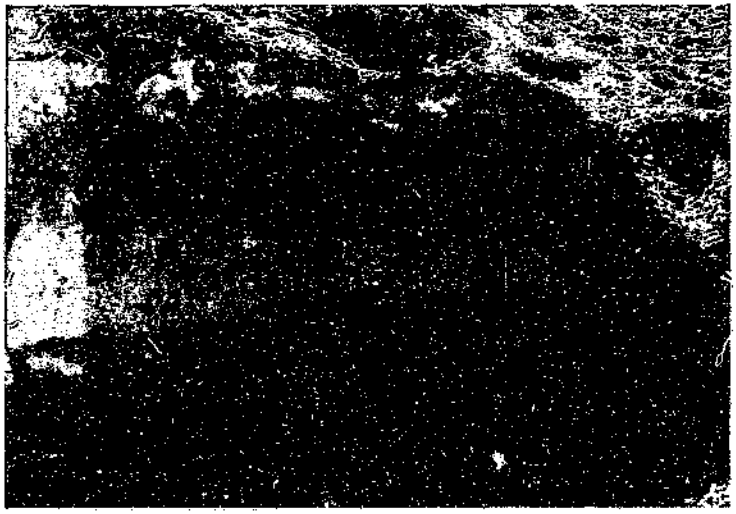


Figure 5.8: Facies structure at Kamberg Cliff showing north south interdigitating fluvial Facies E and aeolian Facies C.

remobilisation along joints. The mottling has been interpreted by Ward (1987) as a product of a hydromorphic processes which would have operated during the emplacement of the Karpfenkliff Conglomerate Formation. Thin dolomite lenses (Fig. 5.11) are sometimes encountered and are interpreted as representing pan facies.

The greyish white sediments of Facies E tend to be closely associated (within a few tens of kilometres) with the current courses of the three major rivers of the study area. Along the Kuiseb, where the sections are best exposed, these deposits fill the northeast to southwest proto-Kuiseb bedrock depression westward to around Gomkaeb.

Figure 5.9: Diagenetic mottling (arrowed) common to Facies E deposits, photographed at Carp Cliff.

Figure 5.10: Tufa coating (arrowed) on Facies E deposits at Kamberg Cliff.

Figure 5.11: Thin Dolomite lenses (arrowed) found within Facies E deposits at Kamberg Cliff.

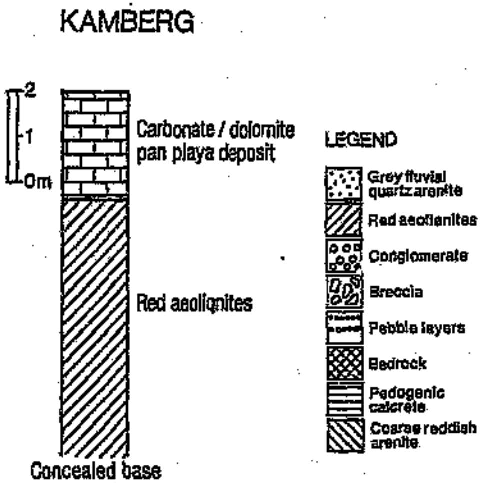


Figure 5.12: Graphic log of deposits of Facies F.

Facies F (Fig. 5.12)

This carbonate facies has been identified as [illegible] of pan deposits by Ward (1987), and compare closely with other simil[illegible] de[illegible] worldwide (Walker and Middleton, 1977). The deposits have a typical [illegible] appearance where they overlie both Tsondab Sandstone and Kuiseb Schist, this being due to differential weathering. Known as the Zebra Pan Carbonate Member, they consist chiefly of dolomite and are greyish to whitish, giving characteristic Rillenkarren textures on weathering (Fig. 5.13), and can reach thicknesses of several metres. They contain gypsum crystal casts (Ward, 1988a) about 0,03 to 0,05 metres in length, as well as prominent desiccation cracks, root casts and burrows all of which often show an infilling of typical aeolian material (Fig. 5.14).

Facies G (Fig. 5.15)

A seventh facies of the Tsondab Sandstone Formation was recognised on the interfluve between the Tsondab and Tsauchab Rivers and has been labelled Facies G in conformity with Ward's (1984a, 1987) system (Fig. 5.16).

These deposits comprise a lateral variant of Facies C, and are made up of a combination of fine, sub-angular to sub-rounded quartz grains with red ferric oxide patinas and coarse, rounded to sub-angular quartz sands with little or no patina. The general colour of the deposits tends to be red brown (5YR). They show strong medium to large-scale wedge planar cross bedding with a predominant westerly azimuth, suggesting a prevalent easterly wind regime. Biogenic components are very common as in the deposits of Facies C. Westerly wedge planar cross bedding and coarse grain influx is common to the modern linear to stellate dune systems of the Sossus Sand Formation along both the Tsondab River and Tsauchab River axes, and is considered to have resulted from the effects of topographic forcing of local and boundary layer wind systems down the valley axes. This axial forcing serves to channel and accelerate easterly winds from east to west creating the typical disruption of dunes across the sand sea visible on satellite images (Fig 4.2).

Figure 5.13: Characteristic Rillenkarren texture of Facies F carbonate-dolomite pan deposits.

Figure 5.14: Dessication cracked surface of Facies F carbonate-dolomite pan deposits of the Zebra Pan Member.

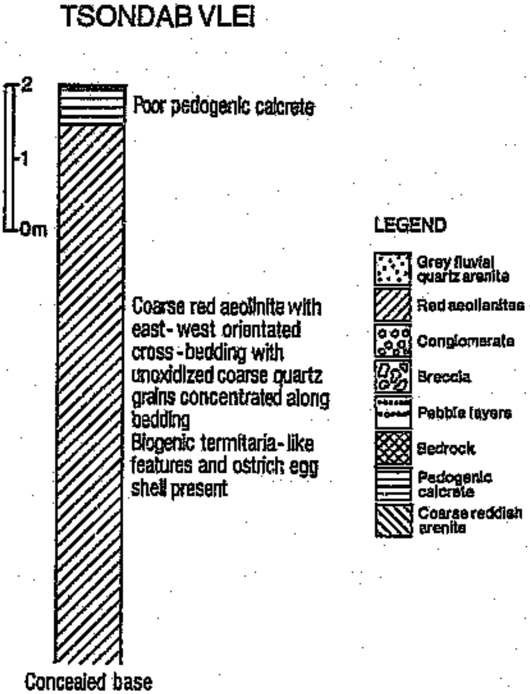


Figure 5.15: Graphic log of a section of Facies G.

Figure 5.16: Characteristic coarse grain cross bedded deposits of Facies G.

The coarse grain influx into the aeolian sediments of Facies G (i.e. the equivalent sands to Facies C) is evidently related to this intensification of easterly wind influences along river axes. The coarse grain sediments can be seen to originate from fluvial input along the river axes where deposition of Facies E type sediments is occurring today. These sediments are reworked by the easterly winds onto the flanks of dunes to the west; in the course of transportation they are winnowed, the fines being removed while the coarse grains saltate/creep across the dunes more slowly and become stranded when the easterly wind dies down or the lower saltation threshold is reached. These coarser lags are then reworked into the common pool of aeolian sand by the prevailing southerly winds. This aeolian input of fluvial sands into the dune system still operates along the Tsondab River (Fig. 5.17) and Tsauchab River (Fig. 5.18). No specific modern analogue of the above could be found along the Kuiseb River, although the same process has been shown to occur with grains weathered from quartzite components of the Karpfenkliff Conglomerate Formation (Fenwick, 1989, 1990) (Figs 5.19, 5.20, 5.21, 5.22, 5.23).

Karpfenkliff Conglomerate Formation

Deposits of this formation, termed calcrete caprock in conjunction with what is now known as the Kamberg Calcrete Formation by Marker (1977a, 1977b), reach thicknesses of up to 60 metres in places especially in the Chausib River (Ward, 1987). The type locality for these deposits is the Carp Cliff mesa (23°20'S; 15°45'E) (Fig. 5.24) in the upper Kuiseb canyon, where Martin and Korn first sought shelter in their desert sojourn during the Second World War. To the north the lithological components of the Karpfenkliff Conglomerate Formation are dominated by Damara metaquartzites and Etjo Formation quartzites, as well as a large input of vein quartz. The clasts are mainly well rounded and are often marked by arcuate percussion scars (Fig. 5.25). Ward (1984b) has interpreted the Karpfenkliff conglomerate as the deposits of a large alluvial fan system.

The relationship of the Karpfenkliff Conglomerate Formation to the Tsondab Sandstone Formation has been recognised by Martin (1950, 1957), Ollier (1977, 1978), Besler (1980), Ward *et al.* (1983) and Ward (1984a, 1987). Ollier (1977,

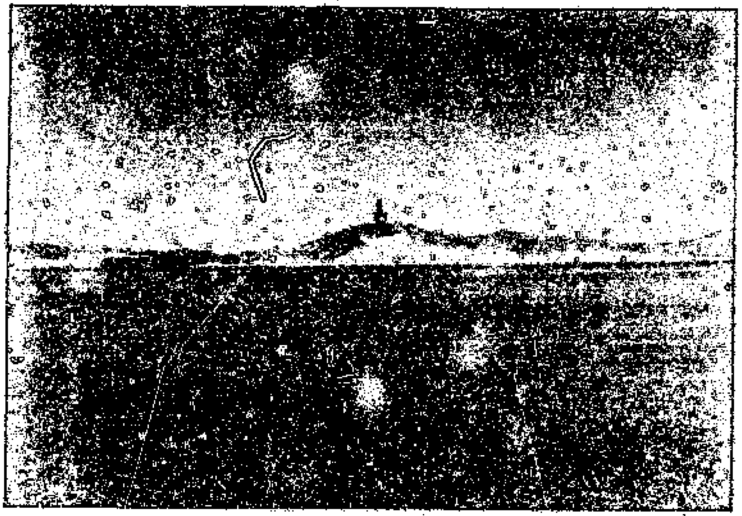


Figure 5.17: Coarse aeolian deposits on flanks of linear dunes (approximately 120 metres high) resulting from aeolian reworking of fluvial sediments along the Tsondab River.

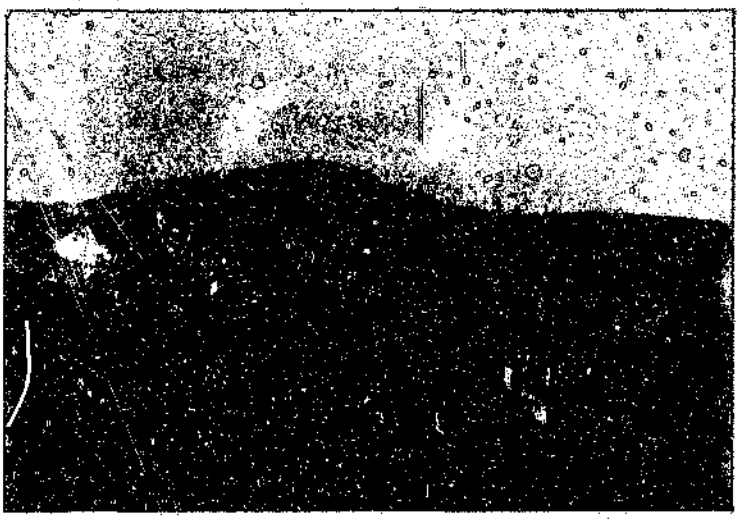
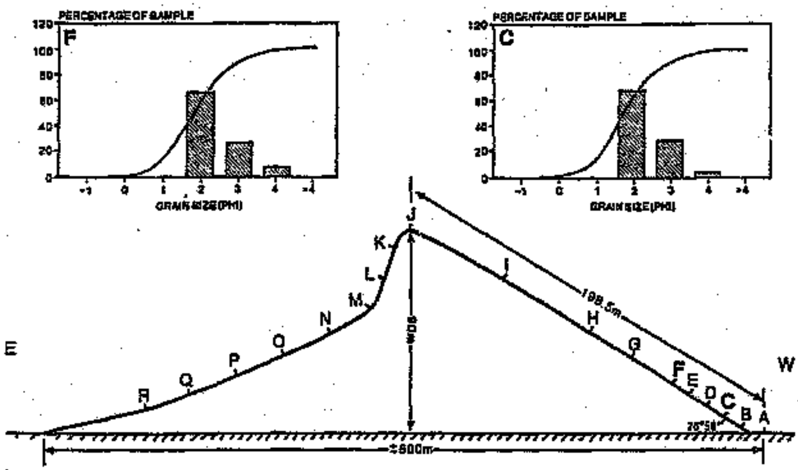
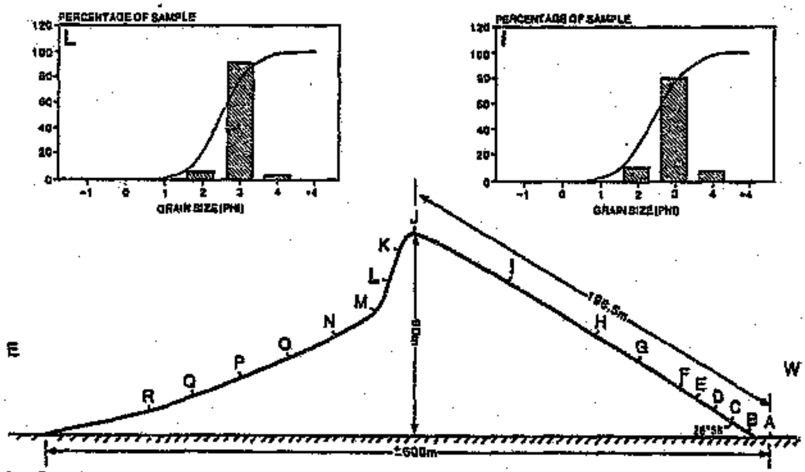


Figure 5.18: Lags (arrowed) of aeolian reworked fluvial sands on the flanks of a star dune (approximately 190 metres high) along the Tsauchab River between Sesriem and Sossus Vlei.



Lag Gravels
Karpfenkliff Conglomerate / Kamberg Calcrete Formation
Tsondab Sandstone Formation
Gomkaeb Basal Breccia
Namib Unconformity Surface

Figure 5.19: Grain size distribution on the lower west plinth of a linear dune Ca. 10km south of Gobabeb.



Lag Gravels
Karpfenkliff Conglomerate / Kamberg Calcrete Formation
Tsondab Sandstone Formation
Gomkaeb Basal Breccia
Namib Unconformity Surface

Figure 5.20: Crest samples of grain size distribution on a linear dune Ca. 10km south of Gobabeb

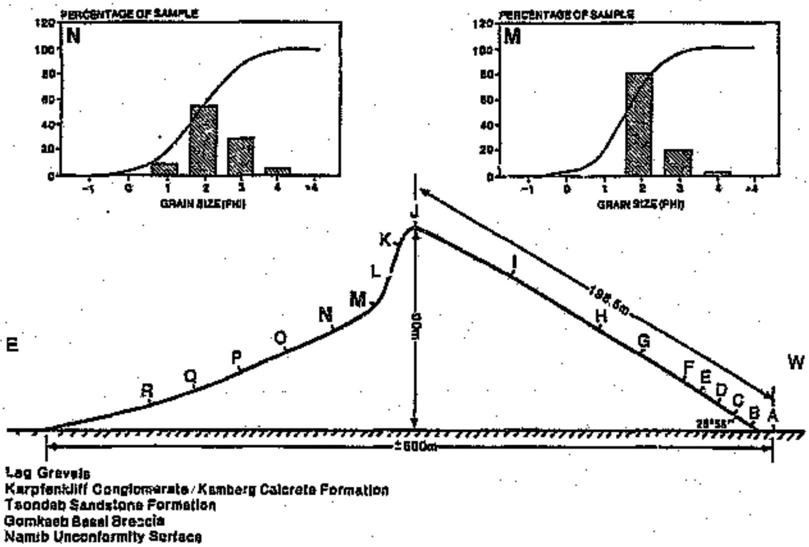


Figure 5.21: Increasingly coarse sand grain distribution on the eastern slopes of a linear dune Ca. 10km south of Gobabeb.

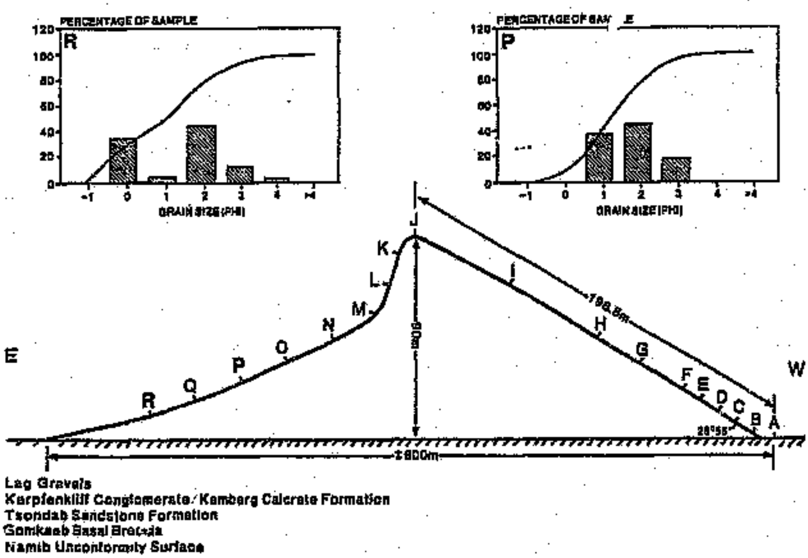


Figure 5.22: Very coarse grain deposits on the eastern plinth of a linear dune Ca. 10km south of Gobabeb.

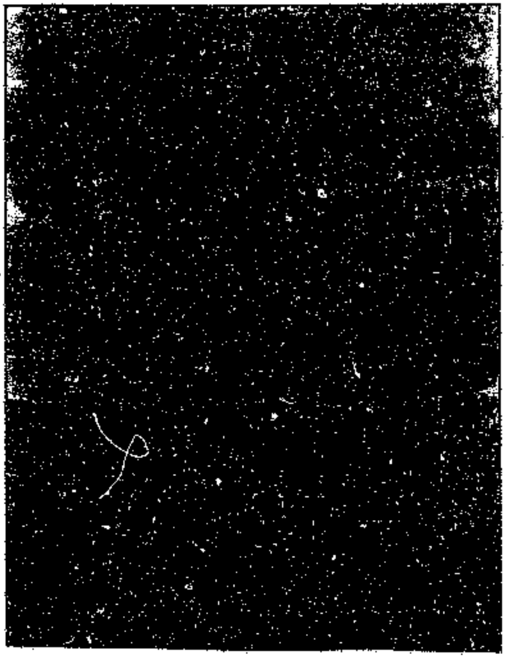


Figure 5.23: Coarse grain mega ripples on the eastern sides of linear dune plinths Ca. 10km south of Gobabeb.

1978) interpreted the combined surface as the *Tsondab Planation Surface* eroded and deposited by a westward flowing palaeo drainage system.

The conglomerates of the Karpfenkliff Formation are a common feature in parts of the eastern Namib desert. They are prominent as markers of the palaeo valleys of the Kuiseb, Tsondab and Tsauchab rivers, as well as in the eastern tributaries prior to the current incission. These deposits are laterally extensive and reach from the Escarpment well into the sand sea, lag gravels in fact extending to within several kilometres of the coast. The main deposits pinch out down the axes of these broad proto-valleys.

A lateral facies of the Karpfenkliff Conglomerate Formation was first recognised in the proto Kuiseb River (23°19'S; 23°52'E) by Ward (1984a, 1987) and named the Koedoe River Breccia. This deposit is similar to the Karpfenkliff Conglomerate Formation, except that the clast components are angular to sub-rounded. Similar deposits have since been found near Onderstеboberg (Hitler Hill) (23°57'S; 15°47'E) (Fig. 5.26) in the Tsondab drainage. The Koedoe River

Figure 5.24: Carp Cliff Mesa, type locality for the Karpfenkliff Conglomerate Formation.

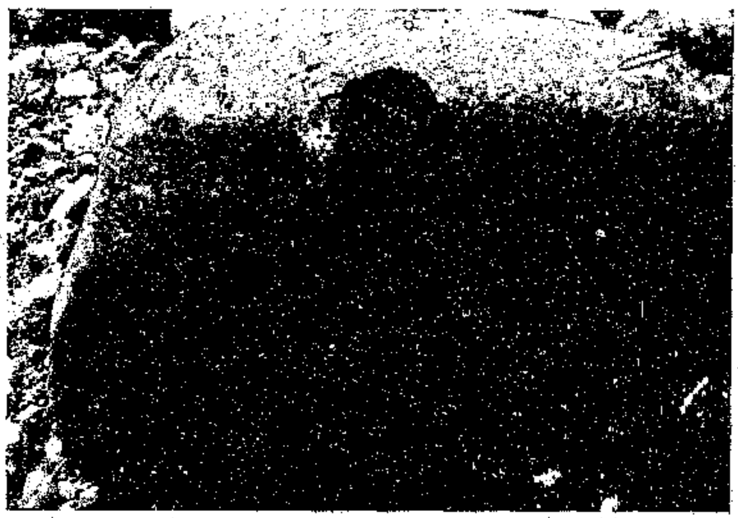


Figure 5.25: Arcuate percussion scars common to cobbles of the Karpfenkliff Conglomerate Formation

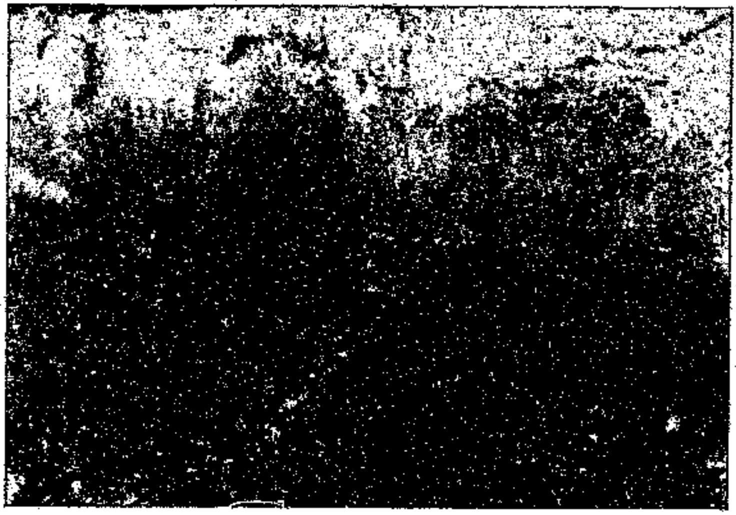


Figure 5.26: Classic Koedoe River Breccia deposits near Onderstebobeg (person for scale).

Figure 5.27: Rip up clast (arrowed) of consolidated/cemented Tsondab Sandstone within the Karpfenkliff Conglomerate Formation at Carp Cliff.

Breccia is closely associated with topographic highs such as inselbergs and prominent ranges of resistant hills, a relationship noted by Ward (1984a, 1987) at 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).

The Karpfenkliff Conglomerate Formation rests throughout on bevelled Tsondab Sandstone or bedrock. It frequently contains rip-up clasts (mainly rounded) of these underlying deposits (Fig. 5.27). The preservation of clasts of Tsondab Sandstone Formation is indicative of a pre-incision depositional hiatus, which permitted these deposits to become cemented/consolidated prior to their erosion.

The Karpfenkliff Conglomerate Formation is best developed near the Escarpment where it reaches a thickness of up to about 60 metres. These carbonate cemented gravels consist mainly of sub- to well rounded clasts showing good evidence of fluvial action in their shape, percussion scars, channel bedforms and clast orientation. The clasts decrease in size westward and are supported in a matrix of angular to sub-rounded quartz sands.

There is crude stratification within the deposits and large clasts are often transversely imbricated. A major upward fining trend is evident, although episodic inputs of coarser clasts are in evidence throughout the succession. Arenite layers, up to 2 metres thick in places, are evident. Channel bedforms are common especially in the Sesriem units (Fig. 5.28). Superimposed upon the major upward fining trend, smaller scale upward fining cycles were noted on a scale of up to 1 metre (Fig. 5.29).

In many exposures the Karpfenkliff Conglomerate Formation contains hardpan and honeycomb pedogenic calcretes in the uppermost portions (Yaalon and Ward, 1982), which have obliterated any sedimentological features (Fig. 5.30).

The main cementing medium in these deposits is calcite, although Ward (1987) has reported dolomite cementation in rare instances. Calcium carbonate precipitated from fluctuating groundwaters has been suggested as the formation

Figure 5.28: Channel bedforms which are moderately common within rudaceous deposits at Sesriem. These are considered to be equivalents of the Karpfenkliff Conglomerate Formation.

Figure 5.29: Minor fining trends within the general upward fining trend of deposits at Sesriem considered to be equivalents of the Karpfenkliff Conglomerate Formation.

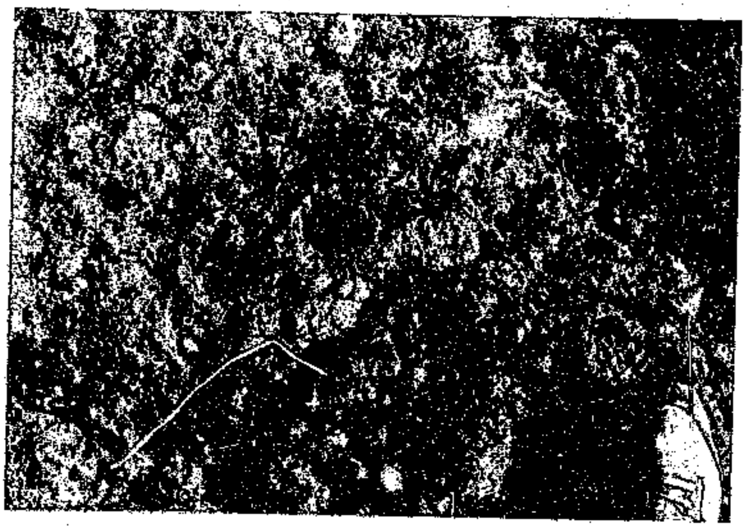


Figure 5.30: Hardpan calcrete developed in upper levels of the Karpfenkliff Conglomerate Formation east of Tsondab Vlei obscures underlying sedimentary features.

process (Yaalon and Ward, 1982). The area is particularly rich in limestones, marbles and dolomites which afford ample sources for the calcium carbonate.

The time lapse between the end of Tsondab Sandstone Formation deposition and the start of Karpfenkliff Conglomerate Formation deposition is unknown. The Tsondab Sandstone Formation has been presumed to be of mid Tertiary age, and the Kamberg Calcrete Formation, which is developed on the aeolianites of the Tsondab Sandstone Formation interfluves as well as in the upper parts of the Karpfenkliff Conglomerate Formation, is thought to be of end Miocene age (Ward *et al.*, 1983). A Miocene age is inferred for other similar Namib deposits (Ward *et al.*, 1983), but, as will be indicated later, the dating evidence is rather tenuous.

The Karpfenkliff Conglomerate Formation, as accepted in this study, is highly variable in both clast size and lithological constituents. Within the northern part of the study area quartzites, rhyolites and andesitic volcanics are most common, whereas in the southern areas Naukluft dolomites and limestones are dominant. Whilst these differences do not strictly allow these deposits to be classed as Karpfenkliff Conglomerate Formation according to original definitions of this deposit, it is felt that allowance has to be made for lateral differences in source material over the wider scope area of this study. Clast size varies throughout, but there is a general trend from cobbles in the eastern areas to pebbles and lag gravels in the west. Lancaster (1984c) has suggested that this is a matrix supported conglomerate with a well lithified calcium carbonate matrix (Lancaster, 1984c: 259) and agrees with Ward (1984a, 1987) that it was laid down by anastomosing and braided streams of a large, low-angle alluvial fan system.

Rooikop Gravels

Limited exposures of gypsiferous deposits containing shells (mainly the oyster *Striostrea margaritacea*) and sands with some cobbles and pebbles occur along the coastal tract of the central Namib. These have been described by Miller and Seely (1976) and Ward (1987) and recognised by SACS (1980). These deposits occur up to about 40 m above present sea level. They overlie granites of the Damaran Sequence as well as consolidated cemented arenites, and are covered by a gypsum crust. Ward (1987) has proposed a littoral depositional environment for these deposits. The occurrence of robust faunal forms seems indicative of warm water conditions, in sheltered water or lagoonal environments (Miller and Seely, 1976; Rust and Wieneke, 1976; SACS, 1980). These gravels can be linked to three beach deposits (D, E and F of the Sperrgebiet) in the southern Namib, which also contain fauna indicative of warm seas (SACS, 1980).

Kamberg Calcrete Formation

The Kamberg Calcrete caps the upper facies of the Tsondab Sandstone Formation on the interfluves and is also present in the uppermost levels of the Karpfenkliff Conglomerate Formation. The calcrete generally displays a highly mature profile, grading from a laminar crust into hardpan, honeycomb and nodular types and then into the Tsondab Sandstone Formation arenites or Karpfenkliff Conglomerate Formation hosts. The type locality for this formation, as proposed by Ward (1984a, 1987) and originally described by Yaalon and Ward (1982), is located south west of Kamberg at approximately 23°36'5"S, 15°39'E.

The lower contact of the Kamberg Calcrete Formation with the Karpfenkliff Conglomerate Formation and the Tsondab Sandstone Formation is gradational, whereas the upper contact is abrupt where overlying aeolian sands of the Sossus Sand Formation are present. The deposit reaches a maximum thickness of about 5 metres. Yaalon and Ward (1982) recognised four main divisions within the profile making up the Kamberg Calcrete Formation. These include a laminar crust up to 0,05 m thick, a hardpan calcrete about 2 m thick, a honeycomb calcrete about 1 metre thick, and a nodular calcrete up to 2 metres thick grading down into the underlying units.

The Kamberg Calcrete Formation has been recorded on several different levels within the area, giving an appearance of several phases of formation. However, on gently sloping substrates the levels can be linked throughout, although Some diachronism is evidenced by the occurrence of first and second order reworked nodules. The lack of large scale cementation within the underlying aeolian arenites may reflect a paucity of local sources for the calcium carbonate. The carbonate was probably introduced by fluvial action associated with the emplacement of the Karpfenkliff Conglomerate Formation, and was then possibly reworked by aeolian action into sterile dune deposits, such as occur within the present day playa of Tsondab Vlei. Blümel (1982) has proposed two alternative sources for the Ubib/Cha-Re area: in the coastal area marine carbonate is available, especially after marine transgressions, to the southerly wind regime, which carries it inland; a second possible source is the Etosha Pan, which could supply carbonate to upper boundary layer airstreams which would then transport it southward.

Cross Section Models

A number of sections have been drawn both latitudinally and longitudinally within the study area (Appendix 1). These sections are based on contours on both 1:250 000 and 1:50 000 scale maps, supported by stereoscopic analyses of air photos. On dune covered surfaces the closest spot heights in interdune areas or major contour crossing points have been used.

North-south sections illustrate clearly the flat surface south of the Kuiseb river recognised by Ollier (1977) as a planation surface. The only major relief on this surface is provided by resistant bedrock inliers and the incised courses of westward flowing rivers, ancient and modern.

East-west sections are of great interest in their confirmation of the conclusion reached from field reconnaissance and aerial photography, that fans associated with these rivers are of a relatively small size, are mainly associated with later formations, and the major ancient courses cut through deposits (mostly of aeolian origin) in discrete channels with aeolianite cliffs on either bank (Fig. 5.31).

Streams and rivers have characteristic skyward convexities in their long profiles. This is probably a result of downstream discharge depletion (Stengel, 1964, 1970; Goudie, 1972) resulting from water infiltration into the porous Tsondab Sandstone Formation, as well as relating to stream competancy in arid areas as is the case for the Kuiseb River which has a bedrock cut channel.

The Reconnaissance Mapping Programme

The mapping carried out by Ward (1984a, 1987) provides intensive coverage of the area around the Kuiseb River. Similar coverage is, however, lacking to the south of this area. To this end a major aim of this project has been the southward extension of Ward's (1984a, 1987) mapping, principally along the main fluvial axes as the intervening areas are largely concealed by deposits of the Sossus Sand Formation.

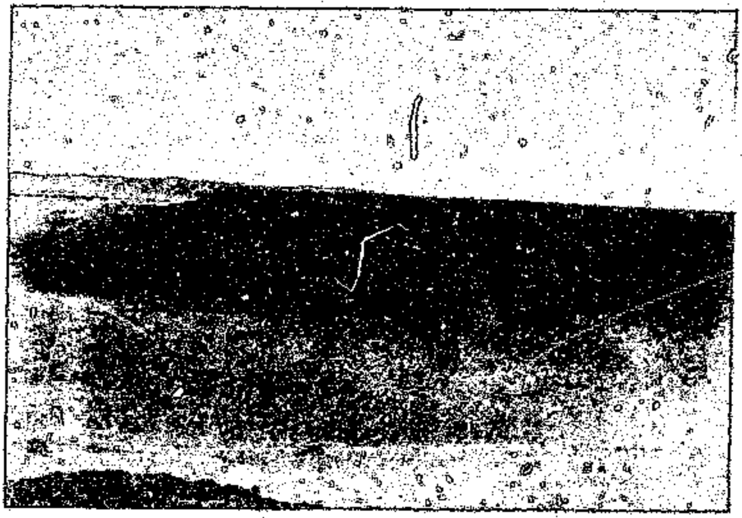


Figure 5.31: The central Namib desert showing the distinctive cliffs of aeolianite Tsondab Sandstone flanking the north eastern course of the Tsondab River. Tsondab Vlei can be seen in the background.

Two Dimensional Sections of Sedimentation in the Central Namib

The two dimensional sections of sedimentation (Appendix 4) in the central Namib desert arising from this study are based on the records of areal mapping and field sections superimposed onto a regional base. Where sections were unavailable, as is unfortunately the case for much of the near coastal areas, surficial mapping with inferred downward projection has had to be used. This approach should not bias the aim of reconciling the two models of sedimentation in the central Namib desert as this relates largely to the distribution of surficial materials between the present linear dune ridges.

Remote Sensing

It has become common, in the last few decades, to use satellite false colour images as an aid to small scale mapping. Landsat images have been used in this study in an attempt to clarify spatial relationships. These images (Figs 4.1 and 4.2) are based upon a reflectance pixel of 82 m x 57 m resolution, which is systemised to a 57 m x 57 m resolution. The corrected data are fed through an optronics coding machine to generate the colour image from the numerical data set.

Processing of satellite images using multispectral analysis, although becoming more widely used by geomorphologists, is less common and its use has not thus far been documented in the central Namib. In order to identify outcrops or sub-outcrops in inaccessible areas, a programme of image enhancement for the study area has been undertaken with the following results.

Images for the northern and southern areas were chosen as follows:

1. DATE. Between 24th March 1984 and 12th December 1989.

2. CLOUDCOVER. Maximum average of 50% for Landsat 5 (MSS).

3. WRS TRK-FRM (Worldwide Reference System Track and Frame):
   179-076 for the northern area
   179-077 for the southern area.

This list (Appendix 3) formed the basis from which to choose the most suitable pairs, these being:

1) 87.12.07 both areas 100% cloudless, and
2) 88.12.25 northern area 100% cloudless and southern area with maximum 10% cloudcover.

Of these the first pair was chosen for final analysis.

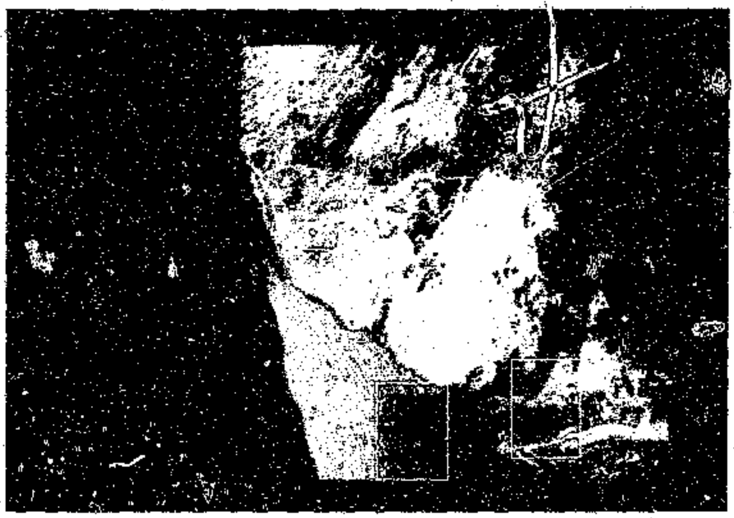


Figure 5.32: Satellite photo of the central Namib showing the signature generation area to the east and the area to the west (Fig. 5.33) onto which these signatures were imposed.

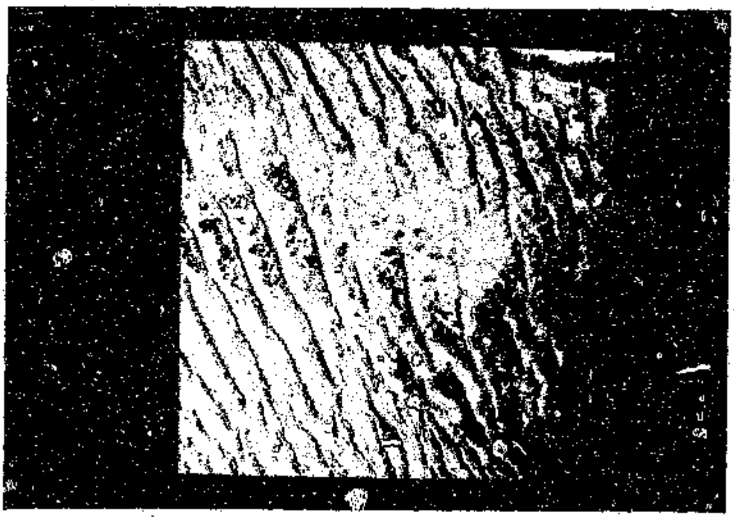


Figure 5.33: The central Namib desert south of the Kuiseb River.

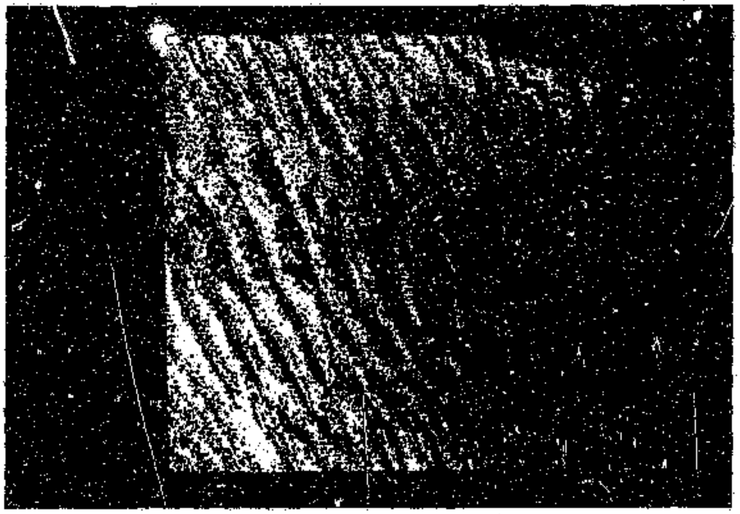


Figure 5.34: Signature enhanced version of figure 5.33.

The technique used involves generating signatures of the various known and mapped deposits to a Gaussian threshold value of 2 for these signatures. These signatures were established for large base areas, the smallest used in this study being 912,83 hectares and the largest being 11 155,91 hectares. Larger area signatures are not a problem to create, except for areal extent limitations, and do not significantly change the results. Once chosen, the data of the signatures were run as scatterplots. These scatterplots showed no statistically significant variance (T. Boyle: pers.comm. 1990). Images of parts of the study area were then regenerated with colour enhanced values for the above signatures (Figs 5.32, 5.33 and 5.34).

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The base data and results of the study have been presented in Chapter 5. Based on these results a discussion is prese d in Chapter 6.

CHAPTER 6

DISCUSSION

The discussion follows the form initiated in enumerating the results covering field observations, reconnaissance mapping, the sections and the remote sensing. The dating of the deposits of the Tsondab Sandstone Formation is also discussed.

Field Observations

Gomkaeb Basal Breccia

The thin deposits of regolith or lithosols making up the Gomkaeb Basal Breccia indicate an *in situ* derivation from the Kuiseb Formation schists (Damara) comprising quartz clasts, mica flakes, garnets and the quartz sand matrix, rather than development in a regressive shoreline situation as has been suggested. The provenance of these deposits is based on analogues from the Khomas Hochland as described earlier. Analogues for the Gomkaeb Basal Breccia can also be found in the southern Namib, the oldest supposedly Tertiary sediments being those of the Chalcedon-Tafelberg Silcrete Formation which are probably dateable to the Palaeocene (SACS, 1980). It can, however, be argued that the Gomkaeb Basal Breccia is of Miocene age (Selby, 1976), particularly if it can be proven that the Namib Unconformity Surface is a Post-African erosional feature rather than King's African surface, as will be discussed later.

Facies B

Although this deposit has been shown to be lithologicaly similar to the Gomkaeb Basal Breccia Member by Ward (1984a, 1987), cross bedding within the strata is suggestive of fluvial deposition (Reading, 1978; Reinek and Singh, 1973). Ward (1984a, 1987) has interpreted these deposits as small alluvial fans but has noted the suggestion by J. McCarthy (pers. comm. to J.D. Ward, 1983) that these deposits and those of the Gomkaeb Basal Breccia could be indicative of a regressive shoreline succession. This scenario could also explain the origin of the carbonate cement. Ward (1987) has countered this suggestion on four main points. Firstly he points out that the Namib Unconformity Surface extends to the Great Escarpment where it reaches 1000 metres in altitude; it has, in contrast, been shown that the maximum Cainozoic sea level on record along the Namibian coast (in the Buntfeldschuh - Bogenfels region) is 170 metres above present level. Secondly the break up of West Gondwanaland was followed by the formation of the Great Escarpment by headward erosion, and the coastal tract was bevelled by pediplanation processes (Dingle and Scrutton, 1974; Martin, 1973; Partridge and Maud, 1987, 1988). Thirdly, Ward (1987) points to the the local derivation of the quartz and garnet components as opposed to the redistributive effects that would generally be expected with marine processes (Ollier, 1977). A further consideration is that spatially contemporaneous deposits are not found on the Namib Unconformity Surface where it transgresses the Salem and Donkerhuk Granites. Also, no marine fossils have thus far been located in these deposits. Fourthly, Ward (1987) points out that the carbonate could originate from calcareous metasediments of the late Precambrian Damara sequence such as marbles and limestones in the Gaub Valley and the limestones and dolomites of the Naukluft Nappe Complex. Further the southerly winds postulated for this period (Ward *et al.*, 1983) would have been able to introduce aerosol carbonates from southerly source regions.

Facies C

The presence of red brown, feric oxide stained, cross bedded aeolianites within this deposit with aeolian grain morphology strongly suggests active dune development and movement in an ancient Namib sand sea of possible early Tertiary or Miocene age. The presence of longitudinal (linear) dunes in the Tsondab Sandstone Formation sand sea is difficult to confirm. Problems in recognising longitudinal dune forms in fossil dune deposits were noted by Rubin and Hunter (1985), who drew attention to the fact that these dunes can move laterally and thus develop unimodal cross bed dip directions (as opposed to bimodal-bipolar dips) and can therefore be confused with transverse dune deposits. Dips within the Tsondab Sandstone Formation tend to have one dominant component in the direction of migration and the opposing dip is reduced or absent.

The occurrence of Acheulean Industry stone implements associated with the deposits of the Tsondab Sandstone Formation was noted with great interest. These can not be used to date the deposits, however, as they are only ever found on top of the deposits and never within them. It is further noted that the tools are always made from large cobbles of the Karpfenkliff Conglomerate Formation type which are not to be found anywhere within the Tsondab Sandstone Formation.

Facies D

Various origins have been postulated for the patterned ground features found in Facies D deposits. Ollier and Seely (1977) proposed that jointing within the lower Tsondab Sandstone was responsible, whereas Besler (1982) and Watson (1980) invoked desiccation of gypsum-bearing sediments as an explanation. Watson (1980) also suggested that the macrofractures were a separate feature which he linked to relict fluvial channels. Ward (1984a, 1987) has proposed a further alternative: cementation of the Facies D deposit was achieved by precipitation from calcium rich waters associated with the deposition of the Karpfenkliff Conglomerate Formation, which is closely associated with these deposits. During precipitation calcium carbonate crystal expansion occurs (Goudie, 1973; Netterberg 1980). Such expansion is thought by Ward (1984a, 1987) to have been the causative factor in the formation of these macro-fractures, i.e. Ward (1984a, 1987) proposes a volume increase as opposed to the volume decrease invoked by Besler (1972) and Watson (1980).

Facies E

The presence of sediments of Facies E closely conforming within the proto Kuiseb Depression to current riverine deposits of the Kuiseb, Tsondab and Tsauchab rivers along with lenses of gravel and pebbles strongly points to the fluvial origin of these deposits. The interdigitating facies have been differently interpreted by Selby (1976), who regarded the red layers and wedges as palaeosols reflecting periods of possible ameliorating climate conducive to pedogenesis (Fig. 5.8 and 6.1). Selby (1976), however, records that the supposed brief mesic periods were too limited for clay or calcrete formation. It should be noted that these reddish units are made up of sands typical of Facies C dune deposits, although they contain more carbonate and sylvite than true Facies C deposits; this was probably a product of the hydromorphic processes associated with the emplacement of the Facies E component and the capping Karpfenkliff Conglomerate Formation. Ward (1984a, 1987) has reported halite and sylvite within these red deposits. The biogenic termitaria like structures common to true Facies C are also found here, and cross stratification is similarly present.

Facies F

These deposits are interpreted in terms of three main origins: firstly the formation of pans in interdunes and bedrock depressions during pluvial events; secondly, the development of pans in the distal reaches of ephemeral watercourses; and thirdly, the dismemberment of watercourses by advancing dunes, as suggested by Ward (1988a).

These deposits of dolomite rich indurated carbonate have also been interpreted as having been precipitated in dolines by Marker (1982). Marker (1982) finds support for this contention in suggestions that the 'Namib Limestone' (= Kamberg Calcrete Formation) was deposited as a fan system, the so called dolines being concentrated along proximal parts of the fan.

Facies G

The aeolian character of these lateral variant facies of Facies C is suggested by the grain morphology of sub-carapace (aeolian reworked coarse fluvial sands) grains and the well preserved aeolian cross bedding found here. The westerly azimuth wedge planar cross bedding within the deposit is strongly suggestive of

Figure 6.1: Facies structure at Kamberg Cliff showing near-horizontal stratification in an east-west direction and interdigitating fluvial Facies E and aeolian Facies C.

dominant easterly wind regimes, as is the case at present along the channels in the area through which boundary layer winds are funnelled generating complex and stellate duneforms.

Karpfenkliff Conglomerate Formation

Martin (1950, 1957) first recognised the alluvial origin of the Karpfenkliff Conglomerate Formation Kuiseb/Gaub facies when living in a sheltering overhang of the deposit. Its fluvial characteristics were confirmed by Ollier (1977) and by Ward (1987: 17) who described it as the "earliest record of a well developed Kuiseb-Gaub drainage system in the central Namib". The presence of interbedded Facies E and C arenites suggests, however, that the shift to more mesic conditions in the eastern parts of the Namib occurred spasmodically over an extended period.

Ward (1984a, 1987) has suggested that the Karpfenkliff Conglomerates in the Kuiseb/Gaub region were deposited as a large alluvial fan below the Escarpment which was possibly further west than today, and which was probably less well dissected. The alluvial processes responsible for the deposits did not, in Ward's (1987) opinion, incise the Namib Unconformity Surface to any great degree. This, together with the unconfined nature of the deposit and its clast size reduction and thinning in a westerly direction, conform to criteria generally accepted for the identification of alluvial fans (Blatt *et al.* 1980; Bull, 1972; Cooke and Warren, 1973; Reading 1978; Selley 1976). The channel forms noted earlier, if accepted as indicative of braided streams, would also lend support to the alluvial fan model (Bull, 1972). The small proportion of clay/silt within the deposits is common to such braided stream environments (Bull, 1972; Selley 1976). Upward fining probably represents decreasing fluvial energy, with periodic high energy flooding. Partridge (1985a, 1985b) and Partridge and Maud (1987) have, however, suggested that fluvial deposition in the mid Tertiary on the west coast may have been influenced by epeirogenic uplift. Lancaster (1984b) has suggested that deposits which are now identified, in this study, as lateral equivalents of the Karpfenkliff Conglomerate Formation as expressed along the Tsondab River, represent the distal deposits of a large low angle fan laid down at the end of a shallow Tsondab valley in the middle Miocene. These deposits were then cemented into a conglomerate during the middle to late Miocene. These events were followed by large-scale erosion to a depth of about 30 metres and the deposition of younger suites of gravel making up the Hamilton Vlei Conglomerates, and finally the Narabeb silts; these units can probably be equated with the Oswater Conglomerate Formation and Homeb Silt Formation respectively in the Kuiseb valley. Deposits that have been correlated with the Karpfenkliff Conglomerate Formation include the Arrisdrift Gravel Formation of the lower Orange River Valley which has been dated to middle Miocene on the basis of its rich, diverse faunal assemblage (Corvinus and Hendey, 1978; SACS, 1980). Hendey (1978) has suggested that these remains indicate a warm mesic woodland environment, but this may, in fact, merely reflect the local influence of the river corridor. The Grillental Beds of the Elizabeth Bay Formation have been placed within the early Miocene (Greenman, 1969; SACS, 1980), while the gravels of the Khan and Swakop rivers were accorded a similar age by Gevers (1936). Calcified deposits of the Middle Ugab valley (Mabbutt, 1952) were linked to the Karpfenkliff Conglomerate Formation by Ward *et al.* (1983). The Catrona Conglomerates in the Angolan Namib have been dated to early Miocene by Soares Carvalho (1961).

Lancaster (1984c) has supported the contention that the Arrisdrift and Lüderitz faunas accumulated at about the same time as the gravels of the Karpfenkliff Conglomerate Formation in agreement with the suggestion by Yaalon and Ward (1982). Lancaster (1984c) has stated that the Capping Conglomerates (= Karpfenkliff Conglomerate Formation) represent the oldest fluvial deposits in the central Namib. This is manifestly not the case, as earlier fluvial phases within the Tsondab Sandstone Formation itself indicate.

Rooikop Gravels

Rust and Wieneke (1976) have quoted radiocarbon dates of between 30 000 and 35 000 Ma for these deposits, although SACS (1980) has drawn attention to the possibility of contamination errors. Although similar deposits in Namaqualand and the Sperrgebiet have been thought to be of a Pleistocene age (Carrington and Kensley, 1969; Haughton, 1931), Hendey (1981) has tentatively placed these within the Miocene on the basis of the warm water evidence. The first upwelling of Antarctic bottom water associated with the Benguela current can be dated with some confidence to the late Miocene (Siesser, 1978, 1980). It would be expected, therefore, that littoral deposits containing fossil marine fauna characteristic of warm oceans would predate the beginning of cold upwelling in the Benguela system.

Martin has reportedly (pers. comm. to Scholz, 1972) postulated that the pedogenic calcrete was formed within a soil and has since been exposed through erosion. Scholz (1972) has inferred that the surface calcrete was formed through the evaporation of rainwater giving rise to a succession of very thin sinter layers. In contrast, the lower nodular calcrete was interpreted as being of pedogenic origin.

Calcrete duricrusts constitute an important stratigraphic marker in the central Namib, particularly in the eastern Escarpment areas. These duricrusts have developed mainly within the upper deposits of the Karpfenkliff Conglomerate Formation and on the Tsondab Sandstone Formation in the interfluve areas. These calcretes were emplaced prior to the onset of recent fluvial incision and major canyon formation (Martin, 1950, 1957; Ollier, 1977, 1978; Ward 1984a, 1987; Yaalon and Ward, 1980). Goudie (1972) also noted that the calcareous horizons within the deposits predate the incision of the major rivers.

The calcrete is believed to be indicative of a period of environmental stability. Yaalon and Ward (1982) have postulated that this period would necessarily have lasted at least several hundreds of thousands of years, under a semi-arid climate with an annual rainfall of approximately 350-450 mm; these conditions were present only in the east and gave way rapidly to the hyper-arid environment encountered today in the western Namib (Besler, 1972b; Schulze, 1969; Ward 1984a, 1987). Ward (1987) has reported the presence of small scale pseudo-anticlines and synclines within the deposits; this is indicative of a high degree of maturity, being the result of growth pressures leading to internal buckling within the duricrust (Goudie 1973; Netterberg, 1969a, 1969b, 1980; Reeves, 1970; Watts, 1977).

The Kamberg Calcrete Formation is definitely younger than the Tsondab Sandstone Formation and probably somewhat younger than the final phases of the Karpfenkliff Conglomerate Formation. Incision of river systems into these deposits was, however, more recent. As has been discussed the deposition of the Karpfenkliff Conglomerate Formation has been placed within the end Miocene, whereas the deep incision of the local rivers is considered by Martin (1950, 1961) Korn and Martin (1957) and Ward (1984a, 1987) to date to end Tertiary times. The emplacement of the Kamberg Calcrete Formation has been assigned an end Miocene age by Ward (1984a, 1987), thus linking it with similar deposits in the south (SACS, 1980). The lack of post depositional solution of these duricrusts implies a return to mainly desertic conditions during the end Tertiary and Quaternary, during which mesic periods were presumably of short duration (Yaalon and Ward, 1982).

Goudie and Wilkinson (1977) have shown that calcretes can occur in areas with precipitation as high as 600 to 850 mm per annum, but develop best in areas receiving less than 500 mm. Netterberg (1980) has shown that optimum calcrete growth occurs at around 350 mm/yr. Gile *et al.* (1966) suggest that calcrete is formed mainly on calcium rich deposits, but also allow that duricrusts can develop on coarse alluvial fan deposits as well as on finer material which need not be carbonate bearing. Blümel (1982) points out that calcretes need not be restricted to a particular type of substratum; the material need only have a permeability sufficient to allow solutional transport of calcium carbonate. He reached the conclusion that the duricrusts of Namibia were generated by allothic aeolian calcium carbonates, i.e. which have been "post- or syngenetically transformed and dislocated by a pedogenic process" Blümel (1982: 71). The pedogenic explanation for the formation of calcrete duricrusts is certainly the most favoured at present (Blümel, 1982; Rohdenburg and Sabelberg 1969, 1973; Sabelberg and Rohdenburg 1975; Werner, 1971).

Blümel (1982) also expressed doubt as to the dating, and although recognising different depositional phases, proposes that the youngest deposits date to the last glaciation (Würm) whilst the slightly older generations have ages greater than 45 000 before present (B.P.). Dating can only be applied to the time and stage of subareal diagenesis and not the period of initiation of precipitation (Subterraneous stage) (Blümel, 1982).

Lancaster (1984a, 1984c) considered that Ward (1984a) and Yaalon and Ward (1982) have placed too great an emphasis on the necessity for a mesic climate for the formation of the pedogenic calcrete. There is, in fact, support for the contention that a state of semi-aridity only was reached; aeolian sediments continued to accumulate at the same time, although it is possible that the rate of deposition of these sediments was reduced (Lancaster, 1984c).

River incision into, and through, the Kamberg Calcrete Formation, the Karpfenkliff Conglomerate Formation, and the Tsondab Sandstone Formation was initiated as a response to late Tertiary to early Pleistocene continental uplift (Korn and Martin, 1957). The greater effect of this downcutting witnessed in the Kuiseb system can probably be attributed to the stream capture on the inland plateau resulting from the breaching of the Great Escarpment (Anon, N.d.)

The Disparate Models

The Low-Angle Fan Model

Besler's (1984) proposal has been extrapolated into a figure in this study as an illustration (Fig. 6.2). This model shows plan proximal and distal sections prior to the emplacement of the Sossus Sand Formation, illustrating the large low-angle fans. Besler's (1984) concept of large alluvial fans marking the end of the Tsondab Sandstone Formation must be treated with caution, as no evidence was found during this study for capping fluviatile or fluvially reworked aeolianites west of the Karpfenkliff Conglomerates as is the case in coastal areas further south (Ward, J.D., pers. comm., 1989; Ward, 1984a) where the uppermost deposits are of aeolian origin.

Besler (1984) and Besler and Marker (1979) have also reported the presence of a younger, cross-bedded sandstone, often containing calcium carbonate nodules found in the form of ridges but never as cliffs. It appears to be less compact and cohesive than the typical Tsondab Sandstone. The morphology and distribution of this variant suggests that it may represent relict dunes derived from weathering of the parent deposit (= Tsondab Sandstone Formation). A particular example noted by Besler and Marker (1979: 158) east of Narabeb and west of Tsondab Vlei (Fig. 6.3) was examined and showed close correlations with the aeolian Tsondab Sandstone facies present along interfluves where

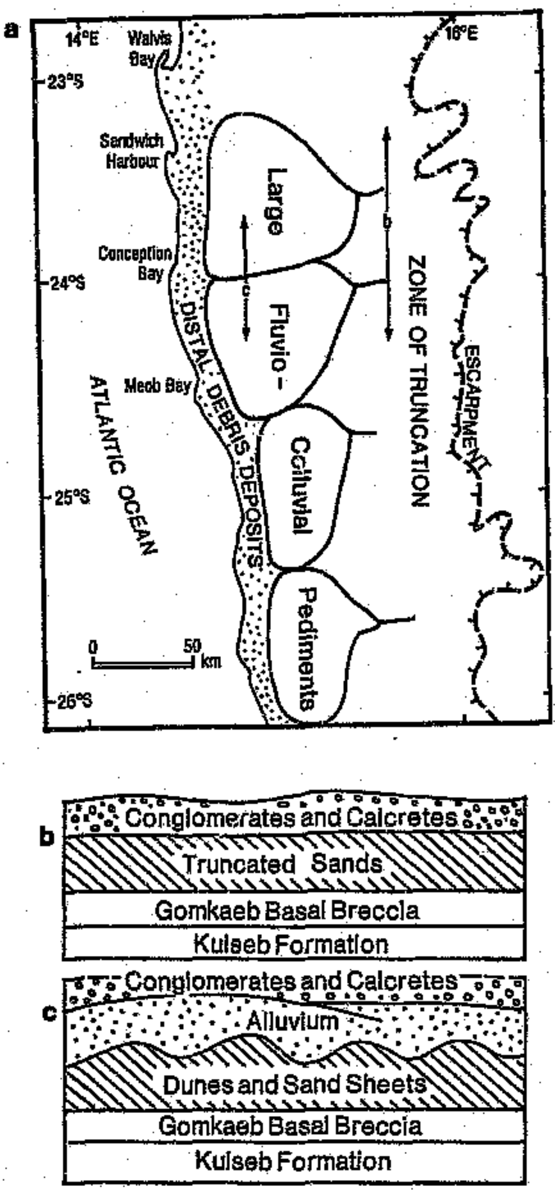

Figure 6.2: Plan (a), proximal (b) and distal (c) cross-sections of the Tsondab surface pre-Sossus Sand. Extrapolated from the Low-Angle Fan Model.

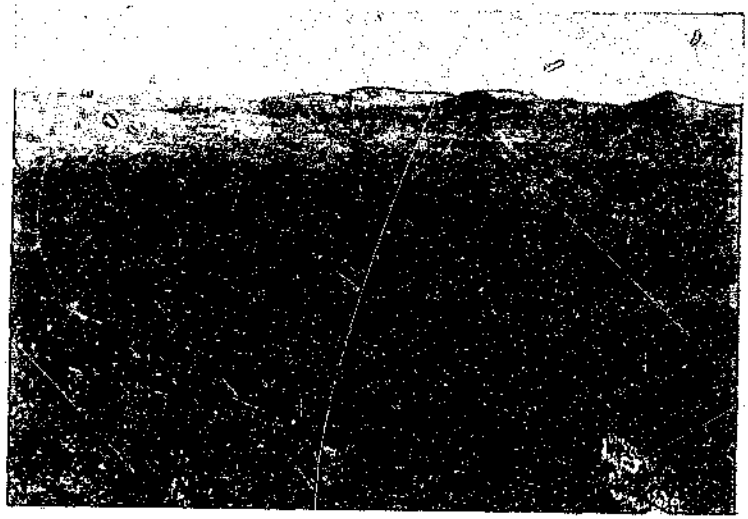

Figure 6.3: The variant sandstone dune (arrowed) of Besler and Marker (1979) east of Narabeb and west of Tsondab Vlei.

consolidation is poor. J.D. Ward (1989, pers. comm.) has also interpreted these deposits as an erosive remnant of Facies C of the Tsondab Sandstone Formation.

The Axial Deposition Model

The conclusions put forward by Ward (1984a, 1987), in what has been termed the Axial Deposition Model in this study and extrapolated into a plan and cross section figure (Fig. 6.4), have been confirmed along the Kuiseb River. This model of sedimentation has now been extended south to the Tsondab and Tsauchab axes where the sedimentary sequences have been shown, in general, to mirror the sequence in the Kuiseb valley, although local variations are evident and an additional facies (Facies G) is present.

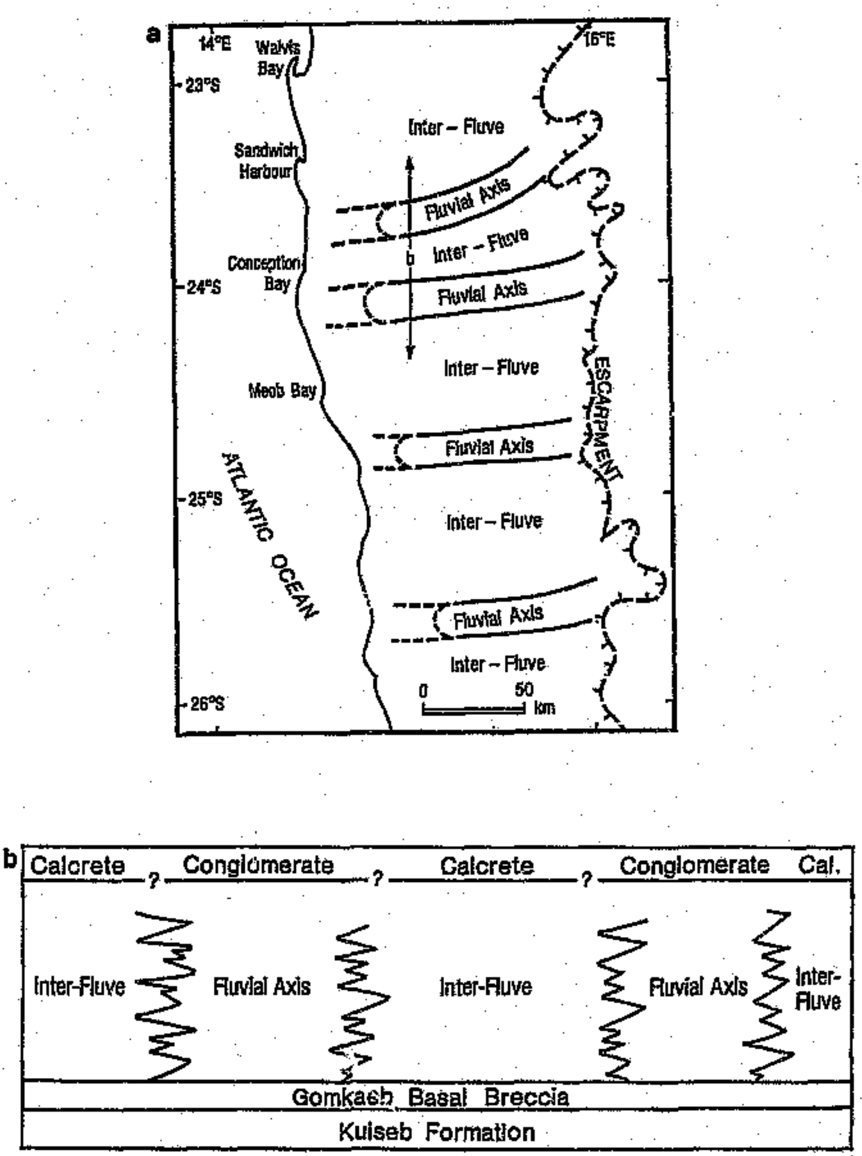

Figure 6.4: Idealised plan (a) and cross sections (b) of the Tsondab Sandstone Formation based on the Axial Deposition Model.

Other applicable studies

Wilkinson's (1987, 1988a, 1988b, 1988c) findings in the Tumas River Valley, to the north of the current study area, have furnished little corroboration for the findings of this study. Of the thirteen events which are thought to have occurred within the Tertiary, only the first seven are seen by Wilkinson (1987, 1988a, 1988b, 1988c) to furnish links with the deposition of the Tsondab Sandstone Formation, Karpfenkliff Conglomerate Formation and Kamberg Calcrete Formation. The deposits in the Tumas River area do not fit into the facies association and sequence of the Tsondab Sandstone, but a basal conglomerate (the Leeukop Conglomerate Formation) rests on the Namib Unconformity Surface and is followed by aeolian and reworked aeolian units with gravel stringers, all of which are covered by up to two metres of sandy gravels which are heavily cemented by gypsum. This deposit may represent a late Tertiary/Quaternary equivalent of the Karpfenkliff Conglomerate Formation

The Reconnaissance Mapping

Extension of the intensive mapping along the Kuiseb River valley to more southerly areas has shown that the distal deposits proposed in the *Alluvial Fan Model* are absent. Two base maps have been created, one (Fig. 6.5) as a reconnaissance extension of Ward's (1984a, 1987) map (Fig. 1.1) and one encompassing the more southerly study area (Fig. 6.6). The reconnaissance mapping has shown also that general depositional sequences were repeated from fluvial axis to fluvial axis during the time of accumulation of the Tsondab deposits a[illegible] deposits. The additional facies that was recorded during the study has been incorporated into this map with outcrop to suboutcrop status. High linear type dunes identified by Lancaster (1989) as compound dunes between the Tsondab and Tsauchab rivers were seen to expose outcrops and suboutcrops of Tsondab Sandstone Formation indicating a higher fossil altitude for these deposits in this area. Large mesas found especially around Tsondab Vlei have been recognised as outcrop grading into suboutcrop in the south.

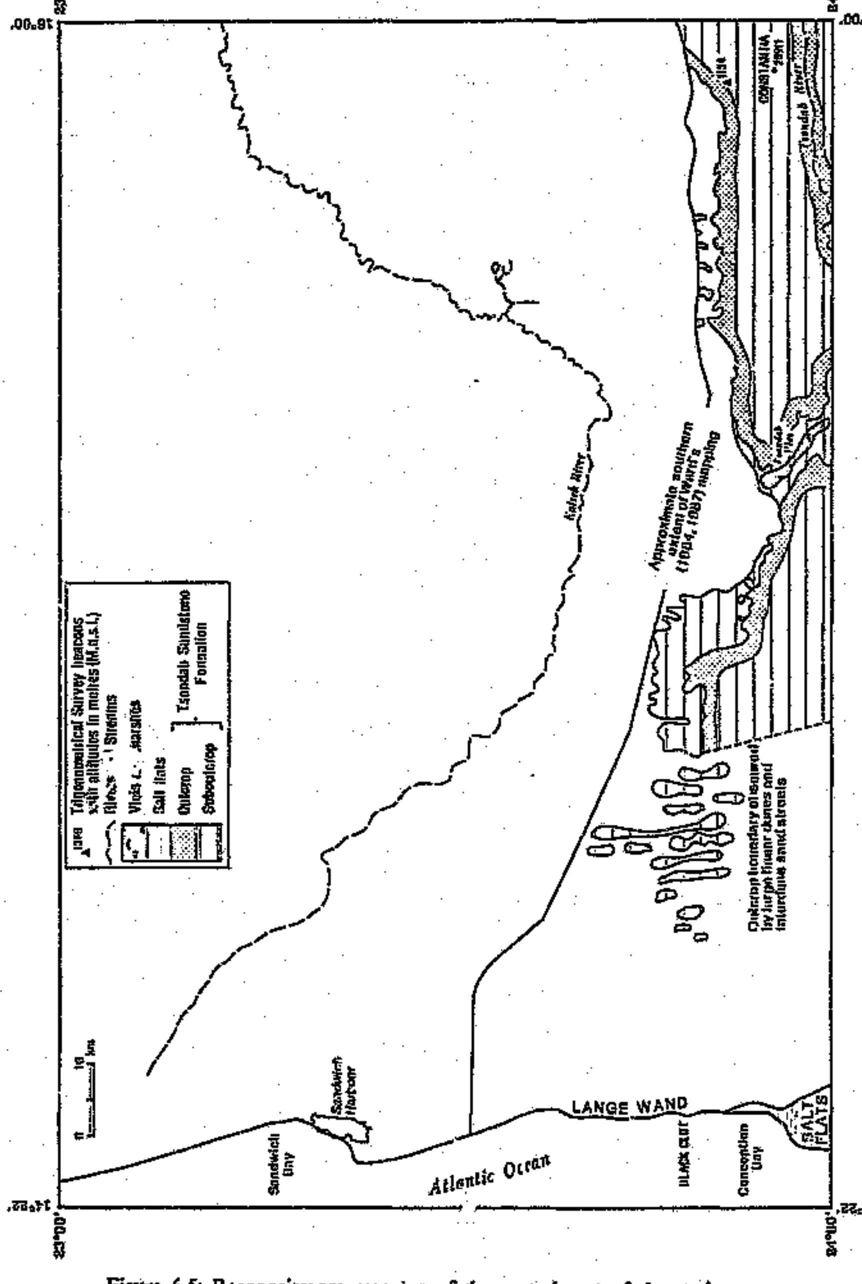

Figure 6.5: Reconnaissance mapping of the central part of the study area around the Tsondab River axis.

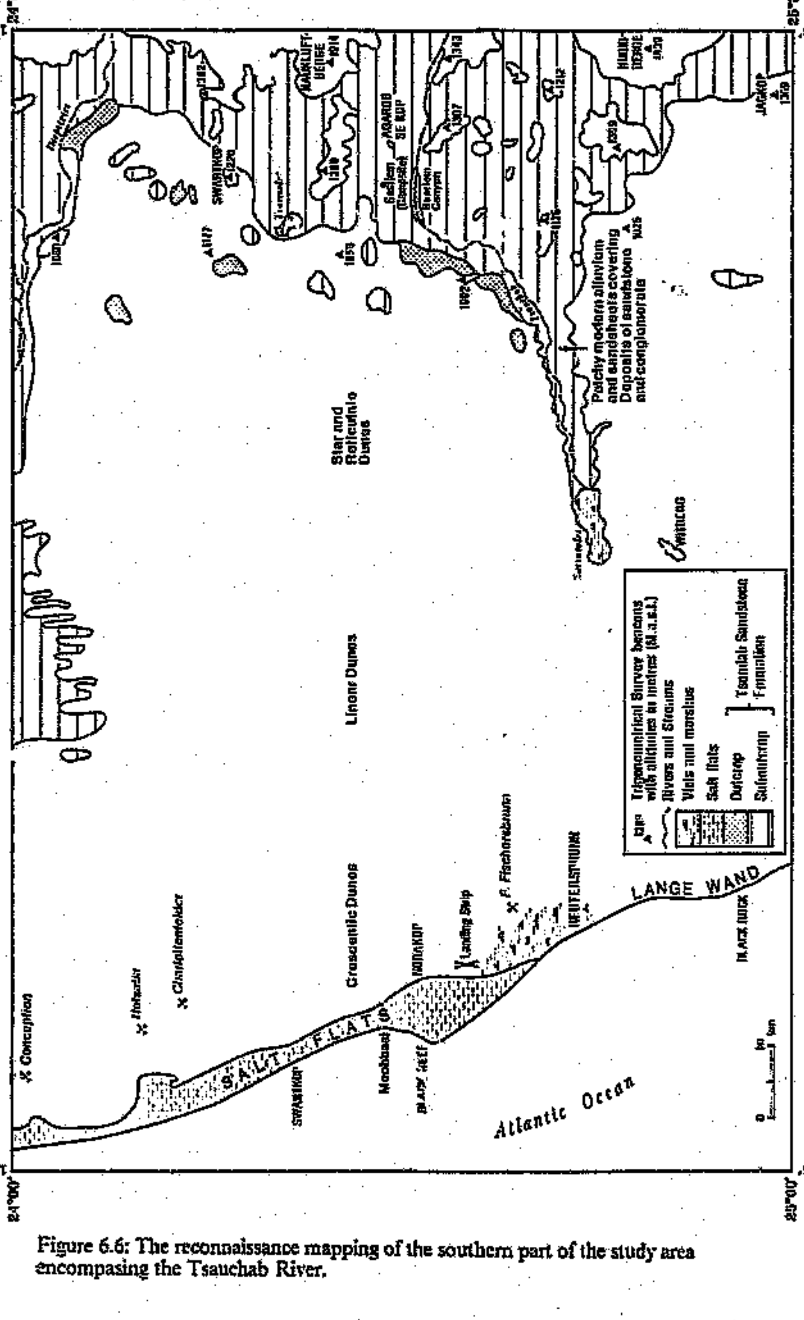

Figure 6.6: The reconnaissance mapping of the southern part of the study area encompasing the Tsauchab River.

The Two Dimensional Sections

The creation of a set of two dimensional sections is a downward extension of the mapping exercise which aims to portray the situation that is believed to have existed at the conclusion of the Karpfenkliff fluvial phase and the Kamberg pedogenic phase.

The sections must of necessity comprise some conjecture when it comes to the illustration of deposits which have been removed during the re-incision of the Kuiseb, Tsondab and Tsauchab Rivers. However, based on the remnants located during the study and a spatial feel for these deposits gained during field reconnaissance, it is felt that Ward's (1984a, 1987) model fairly represents the probable appearance of the Tsondab Sandstone Formation and Karpfenkliff Conglomerate Formations towards the end of deposition. The development of the Tsondab Planation Surface is thought to have been associated with the active fluvial regimes of the Karpfenkliff phase and the effects of the pedogenic Kamberg Calcrete phase.

Remote Sensing

As can be seen from the remote sensing illustrations the similarity of the deposits of the Tsondab Sandstone to modern deposits of the Sossus Sand Formation leads to an extremely complex image, which was deemed to be of little use in this study. The enhanced picture (Fig. 5.33) comprises a total of 262 144 pixels of which 226 889 are unclassified, 4743 are identified as calcified conglomerates, 4961 as calcretes, 23 868 as fluvial deposits and 1953 as aeolian deposits. Reference to the base illustration (Fig. 5.31) indicates immediately that the figure for aeolian deposits is incorrect. Examination of the images leads to the conclusion that surface enhancement processes are grouping outcrops of Tsondab Sandstone with the sunlit sides of Sossus Sand dunes, and fluvial features with the darker sides of Sossus Sand dunes. The identification of conglomerate signatures seems, in some cases, to be more successful. It may be concluded that satellite image processing is of little use where an ancient sedimentary deposit is similar to and in juxtaposition with a modern equivalent.

Figure 6.7: Single spectral band green for the central Namib Desert.

Figure 6.8: Single spectral band red for the central Namib Desert.

Figure 6.9: Single spectral band 3 infra red for the central Namib Desert.

A somewhat more useful result was achieved through the creation of images from single spectral bands (Figs 6.7, 6.8, 6.9), in which contrasts based on single colour reflectivity provided better differentiation.

Dating

The main quest for knowledge on the age of the Namib has come from researchers concerned with the evolution of the specific character of its fauna and flora (*inter alia* Endrödy Younga, 1978, 1982; Koch, 1961, 1962; Seely, 1978, 1984; Seely and Low, 1980; Tankard and Rogers, 1978; Van Zinderen Bakker, 1975). Koch (1961, 1962) was one of the first scientists to postulate that the Namib is an 'old' (Cretaceous) desert based on the diversity and adaptation of the endemic fauna.

Siesser, (1978: 105) has supported a younger age for the Namib "... it is suggested that major cooling upwelling of the Benguela in early late Miocene times initiated aridification of the Namib desert." He concludes that "evidence presented ... suggests that major cooling of the Benguela only became prominent in late Miocene times, and rapid onshore desiccation probably followed" (Siesser, 1978: 112). Van Zinderen Bakker's (1975) Oligocene age for the beginning/intensification of aridity in the Namib is supported by the findings of Shackleton and Kennett (1975) who have shown that Antarctic bottom water temperatures first dropped to their present lows at that time.

Ward *et al.* (1983) have, however, pointed out that the cold Benguela Current is not a necessary prerequisite for arid conditions to prevail in the central Namib. Further Stocken (pers. comm. to J.D. Ward, 1987) has noted that remnants of the end Cretaceous surface of the southern Namib are not everywhere deeply leached and kaolinized (Ward, 1987), although such features, in association with silcrete duricrusts, occur widely on these remnants (T.C. Partridge and R.R. Maud, pers. comm., 1989). The presence of a very thick wedge (c. 4 km) of Albian-Maastrichian sediments in the Walvis basin offshore of the central Namib (Dingle and Scrutton, 1974; Ward, 1987) gives some support for placing the main period of erosion prior to the formation of the Namib Unconformity Surface within the Cretaceous. In addition, the incision of canyons by the larger rivers has been dated, albeit tenuously, to the end Tertiary (Korn and Martin, 1957) by analogy with the deep incision of other southern African rivers (King, 1951, 1953; Partridge and Maud, 1987).

Dating of the final stages of arenite deposition may be possible through palaeontological means. Within the upper layers of these deposits (and perhaps deeper) clear fossil golden mole-like trails are preserved. These indicate the presence of a creature similar to the dune inhabitant of the present day. There is a possibility of dating genetically the time span for the diversification of these creatures from their main family line (D. Ward, pers. comm.). It should be noted, however, that most contemporary mammal lineages developed within the last 20 million years (R.R. Maud., 1990, pers. comm.; Smithers, 1983).

The succession within the central Namib illustrates several different sets of environmental circumstances. The skeletal nature of the Basal Breccia resting on the Namib Unconformity Surface, together with the lack of weathering penetrating into the the underlying Precambrian schists of the Damara sequence is indicative of arid conditions (Ollier, 1978; Selby, 1977; Ward *et al.*, 1983; Ward 1984a, 1987). In this it contrasts notably with the deep weathering and silicification of most remnants of the African surface preserved in areas to the south of Lüderitz, below which the Namib Unconformity Surface has been cut (T.C. Partridge and R.R. Maud, pers. comm., 1989). The subsequent accumulation of arenaceous sediments of the Tsondab Sandstone Formation is illustrative of desertic conditions, with various facies representing dune seas and sand sheets, as well as ephemeral watercourse and pan/playa deposits. Moister conditions seem to have prevailed in the western uplands, leading to the widespread accumulation of pan/playa deposits.

A prevailing southerly wind regime can be shown to have been in force by reference to cross-stratification in the palaeodune deposits. The distribution of the fluvially reworked arenite facies indicates that there was perhaps less water available from the Escarpment than today, as deposits of this kind extend only as far as Gomkaeb in the Kuiseb River valley, and slightly further west than Tsondab Vlei in the Tsondab valley. The westward extent of these sediments in the Tsauchab was intermediate, reaching towards the present Sossusvlei; the actual extent, however, could not be accurately determined due to lack of downcutting into the conglomerates.

Dating of the Tsondab Sandstone has proved to be contentious. Besler and Marker (1979) effectively evaded the issue by assigning the deposits a Tertiary to Recent age, a range since adopted by SACS (1980). As Siesser (1978: 106) has asked, "What unequivocal evidence do we have which indicates the age of this desert?". Ward's (1984a, 1987) contention that the pre-incision deposits of the central Namib are of early Tertiary age is based upon the assumption that the incision of these rivers is a response to epeirogenic uplift in the late Tertiary, a proposal first postulated by Korn and Martin (1957). Partridge and Maud (1987) have shown that major uplift occurred in the south-eastern hinterland of the subcontinent also in Pliocene times; smaller movements characterised the west coast area.

Lancaster (1984c) accepted that the Tsondab Sandstone Formation represents the remains of a massive sand sea made up of sand sheets, dunes and fluvio lacustrine deposits which accumulated during the Palaeogene. The lack of fossils is, however, a major problem in the dating of these deposits. Three biologic traces were encountered during this study. Firstly, termitaria-like features are common, but provide no real dating evidence. Secondly fossil ostrich egg shells (resembling *Struthio oshanai*) (J.D. Ward, pers. comm., 1989, - identified by Sauer) have been found; however, these offer little dating potential, giving the deposits an age by relation only. Thirdly, traces of a golden mole like creature have been encountered (Fig. 6.10). These trails are very similar to those of today. Genetic differentiation calibration has been attempted in various parts of the world (D. Ward, 1989, pers. comm.) and could possibly provide an age estimate for these deposits. A possible dating technique suggested by Ollier (1977) for use on the Tsondab Sandstone Formation is palaeomagnetism; the sands of some of the facies carry a good oxide patina, which might permit a magnetostratigraphy to be established. The only other way of dating these deposits is by way of their boundary relations.

Coetzee (1978a, 1978b, 1980), like Van Zinderen Bakker (1975), also reached the conclusion that the onset of extreme aridity along the Namibian and western Cape coasts was inextricably linked to the evolution of Antarctic glaciation. Coetzee's (1978a, 1978b) analyses of pollen supported Tankard and Rogers (1978) contention that major aridification of the subcontinent dates from the Pliocene. Coetzee (1978a) also guardedly raised the possibility that arid conditions over the sub-continent could date further back than the onset of cold upwelling. More recently Van Zinderen Bakker (1984) has supported a late Miocene age for the onset of aridity and has linked its origin to fully fledged upwelling within the Benguela system. This latest proposal is based upon palynological evidence from Deep Sea Drilling Project holes 532 and 530, leg 75.

Ollier (1977: 211) has suggested a "pre-upper Cretaceous and or Jurassic" age for the Namib Unconformity Surface. He further suggested that after their

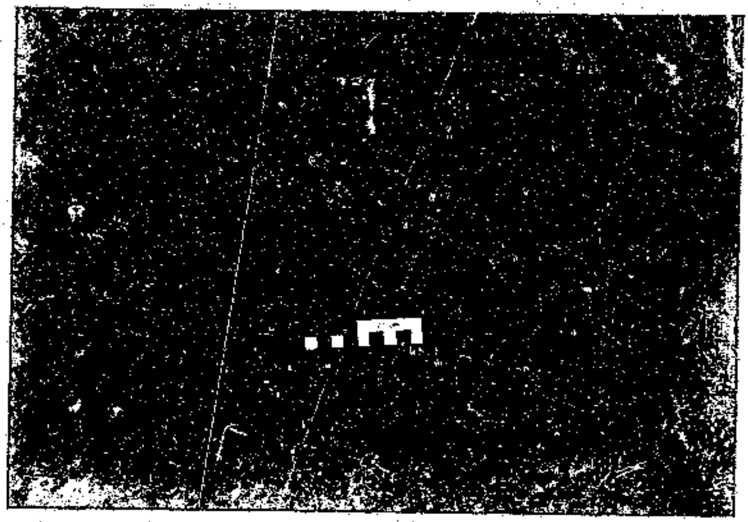

Figure 6.10: Burrows of a golden mole like creature (arrowed) within the aeolian facies of the Tsondab Sandstone Formation south of Swartbank.

accumulation a new erosion surface was cut across the deposits making up the Tsondab Sandstone Formation. This erosion surface was referred to as the Tsondab Planation Surface, described as a "vast pediment" (Ollier, 1977: 208) which stretched from the Escarpment to the Atlantic Ocean. Ollier (1977) saw the Tsondab Planation Surface as a second distinct datum in the geomorphic history of the area "separating the period of accumulation of the Tsondab Sandstone Formation from the later history of fluvial erosion and wind deposition" (Ollier, 1977: 208). He visualised the subsequent emplacement of the Karpfenkliff Conglomerate Formation as a period of sheetflood deposition, these thick deposits then being cemented into conglomerates. The Gomkaeb Basal Breccia has been assigned a Tertiary age because of an apparent correlation with the Tafelberg Quartzites (Ward *et al.*, 1983). The Tsondab Sandstone Formation has been equated (Martin, 1950) to aeolianites of the Upper Buntfeldschuh Formation, in the southern Namib. These aeolianites overlie mid-Eocene marine sediments and are capped by end-Miocene pedogenic calcretes (Stocken, pers. comm. to J.D. Ward, 1987).

The Karpfenkliff Conglomerate Formation has several age interpretations. Ward (1984a, 1987) and Martin (pers. comm. to J.D. Ward, 1981) have postulated an early to mid-Miocene age for these deposits, whilst the pedogenic calcretes capping the interfluves have been equated to similar duricrusts of end-Miocene age in the southern Namib (Ward *et al.*, 1983; Ward, 1984a, 1987).

Ollier (1977) has associated the calcretes capping the Precambrian schists to the north of the Kuiseb and on outcrops in the western part of the study area with the "Basement Conglomerate". However, the Kamberg Calcrete Formation on the Tsondab Sandstone Formation is identical to that developed directly on the Damaran bedrock, and the Gomkaeb Basal Breccia shows no signs of pedogenic calcrete development, although it is thoroughly permeated by carbonate. Further, the calcretes developed on the Damaran metasediments have few or no breccia components. These deposits on examination turn out to be the deposits of Facies F Zebra Pan Carbonate Member discussed earlier. Ollier's (1977) linkages are therefore questioned.

A late Cretaceous age has been postulated for the formation, or exhumation, of the Namib Unconformity Surface by others (Martin, 1950, 1973, 1975; Ollier, 1977; Ward *et al.*, 1983; Ward, 1984a, 1987). Partridge (1985) and Partridge and Maud (1987, 1989) have, however, recognised the Namib Unconformity Surface as a mid Miocene planation surface. Partridge (1985) also drew attention to the weak development of the Benguela Current during the middle to late Oligocene, accepting available palaeontological evidence that the system only intensified and became fixed during the late Miocene. The intensification of this system is linked to the stable circulation of the South Atlantic Anticyclone as a main cause of aridification; these factors are seen by Partridge (1985) as being responsible for the conditions which led to the emplacement of the aeolian Tsondab Sandstone Formation. Partridge (1985) further postulated that maximum aridity within the area did not occur in pre-Miocene times as has been suggested by some, but during the Pleistocene, when the present Sossus Sand Formation accumulated.

Partridge (1985) and Partridge and Maud (1987) have suggested that planation continued relatively continuously from the time of continental rifting until the mid Tertiary. They also point out, however, that the resulting surface is generally capped by thick ferruginous or siliceous duricrusts beneath which deep kaolinized profiles are developed (Partridge and Maud, 1989). Such deep weathering and duricrusts are, however, absent on the Namib Unconformity Surface. Partridge (1985) sees the planation of the Namib Unconformity Surface as commencing with mid-Tertiary uplift of the subcontinent, an uplift that was associated also with a westerly tilting. Partridge and Maud (1988) cite the early to mid Tertiary deposits from Arrisdrift, Elizabeth Bay and Bosluispan as evidence that mesic conditions were in operation in these areas during the mid Tertiary. They have recently noted the presence of a regionally extensive silcrete duricrust capping deep weathering profiles under a well planed surface (the African Surface) marking the Cretaceous-Tertiary (K-T) boundary and dating no younger than the Palaeocene; remnants of this surface are still preserved owing to the lack of Neogene modification in parts of southern Africa. In Namibia Partridge and Maud (1989) have recorded this surface underlying the Buntfeldschuh Formation and the Langental Beds south of Lüderitz.

Partridge and Maud (1988) indicate that the Namib Unconformity Surface is cut below kaolinized and silcrete capped remnants of the African surface, and represents a major cycle of planation which removed all of the original African Surface in the central Namib. The Namib Unconformity Surface is, in their view, referable to the Post-African 1 cycle resulting from early to mid-Miocene uplift and tilting. Partridge and Maud (1989, pers. comm.) have, through altimetric studies, concluded that, in the southern Namib, remnants of the African Surface have a tectonically induced southerly gradient. This inclined surface is deeply dissected and is absent to the north of Lüderitz, where it gives way to the lower Namib Unconformity Surface (Fig. 6.11). The lack of a deeply kaolonized and silicified surface underlying the Tsondab Sandstone Formation confirms the correlation of the Namib Unconformity Surface with the Post African 1 surface. Late Miocene intensification of upwelling in the Benguela system then led to aridification and emplacement of the dunes, sand sheets and ephemeral watercourse deposits which make up the Tsondab Sandstone Formation. Partridge and Maud (1988) also believe that the maximum extension of the

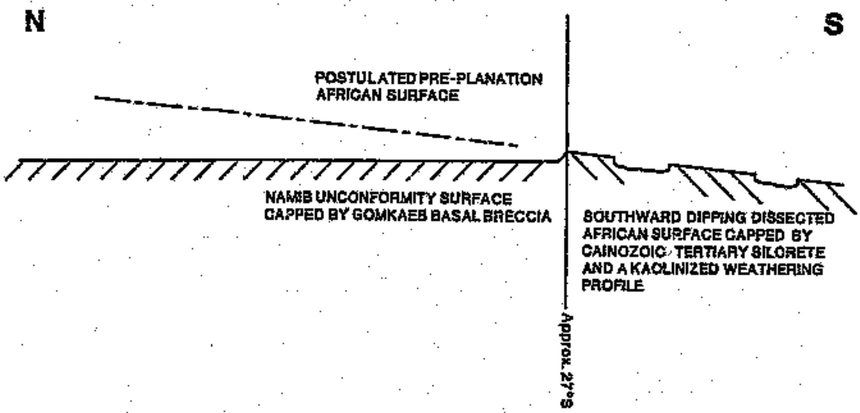

Figure 6.11: Relationship of the Namib Unconformity Surface to the African surface stylised after Partridge and Maud (1989, pers. com.)

Namib Sand Sea (= Sossus Sand Formation) occurred during the Pleistocene. This would allow up to fifteen million years for the deposition of the considerable thicknesses of terrestrial sediments that make up the Tsondab Sandstone Formation, the cementation and diagenesis of these sediments, planation to form the Tsondab Planation Surface, the emplacement of the Karpfenkliff Conglomerate Formation with subsequent development of the Kamberg Calcrete Formation, and subsequent erosional and aggradational events associated with the downcutting of the major fluvial channels in the area.

Two main dating frameworks can thus be set up (Table 6.1). The choice of which is correct must await further evidence and hopefully the acquisition of dateable material.

Table 6.1: The two main chronological frameworks for the Tsondab Sandstone and associated Formations.

"OLD ARGUMENT" Ward *et al* (1983)	DEPOSIT	"NEW ARGUMENT" (Partridge, 1985; Maud and Partridge 1988)
Middle to Late Miocene	Kamberg Calcrete	Pliocene, Pleistocene
Early to Middle Miocene	Karpfenkliff Conglomerate	Upper Pliocene
Oligocene-Eocene	Tsondab Sandstone	Mid to Late Miocene
Palaeocene	Gomkaeb Basal Breccia	Mid Miocene

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A discussion based on earlier chapters has been presented in Chapter 6 together with an extensive discussion of the dating problem associated with the Tsondab Sandstone Formation. These all lead to the conclusions reached in Chapter 7.

CHAPTER 7

CONCLUSIONS

The work undertaken within this study through mapping, topographic interpretation, areal analysis and satellite image processing along with intensive literature reviews, has led the author to the conclusion that what has been termed the Axial Deposition Model in this study, not only explains the depositional sequence along the Kuiseb axis but can be extrapolated to deposits throughout the study area. The Low Angle Fan Model is problematical because, although near Escarpment erosion (Randfurche) is strongly evident, distal alluvial fans are absent. The only large, well developed alluvial fans are those of the Karpfenkliff Conglomerate Formation, which are notably absent in distal areas, and in addition, are mainly cobble conglomerates with little sand input, and are found mainly in proximal near-Escarpment areas.

The origin of the sands of the Tsondab Sandstone Formation is a controversial issue. Local sources from which to derive such substantial quantities of sand do not exist in the form of erodable sedimentary strata. The three most likely sources are fluvial input from erosional retreat of the Great Escarpment and high lying interior regions, coupled with inshore aeolian transport of sands exposed during marine regressions, and longshore drift of sands from the Orange River mouth.

The surface form of the Tsondab Sandstone Formation and reference to standard models of desert landform development in northern deserts seems to have been the main factor which led Besler (1980) to propose what has been termed in this study the Low Angle Fan Model. The surface is, however, mainly a planation feature, a fact recognised by Ollier (1977); it shows evidence of large scale erosion with only minor depositional modification. This planation is thought to have been slightly earlier or contemporary with the Karpfenkliff fluvial phase, which in any case occurred after consolidation of the Tsondab Sandstone. The results of this study suggest the existence of a large-scale repetitive facies sequence in the central Namib, as originally proposed by Ward

(1984a, 1987). This sequence is shown to be duplicated along all of the fluvial axes of the study area.

Satellite image processing was used in the study but was not found to be a technique applicable to the study of sedimentary bodies when these are partially mantled by deposits of a similar nature, and where lighting angle and intensity interferes with the results.

Dating of the deposits of the Tsondab Sandstone Formation remains a matter of debate. Although not tackled as a major problem in this study, a fairly intensive review has been undertaken and presented as a discussion in Chapter 6. Before any final conclusion can be reached about the dating of the Namib Unconformity Surface, Tsondab Sandstone Formation, Karpfenkliff Conglomerate Formation, Kamberg Calcrete Formation and subsequent events, detailed exploration of the whole extent of the deposits with a major aim of discovering dateable deposits will have to be undertaken.

Cursory examination of deposits to the south of the study area was undertaken between the Tsauchab River and Lüderitz-Aus road in the proximal areas and showed no significant differences when compared to the cyclical deposits of the study area. Detailed investigation of these deposits is also recommended.

REFERENCES

Alimen, M.H., Buron, M. and Chavaillon, J., 1958: Characteres granulometriques de quelques dunes d'ergs du Sahara nord-occidental, *Academie des Sciences, Paris, Comptes Rendus*, 247, 1758-1761.

Acon, n.d.(*ca.* 1982): Geological setting: outline of the geological history of the Kuiseb valley west of the Escarpment.

Barnard, W.S., 1973: Duinformasies in die .. ·trale Namib, *Tegnikon*, 2-13.

Barnard, W.S., 1975: Geomorphologiese prosesse en die mens: die geval van die Kuisebdelta, S.W.A., *Acta Geographica*, 2, 20-44.

Besler, H., 1972a: Geomorphologie der Dünen, *Namib und Meer*, 3, 25-35.

Besler, H., 1972b: Klimaverhältnisse und klimageomorphologische Zonierung der zentralen Namib (Südwestafrika), *Stuttgarter Geographische Studien*, 83.

Besler, H., 1975a: Der Namib-Erg und die südafrikanische Randstufe, in L. Beckel and S. Schneide·, *Die Erde neuentdeckt*, Mainz.

Besler, H., 1975b: Messungen zur Mobilität Dünensanden am Nordrand der Düne-Namib (Südwestafrika), *Würzburger Geographische Arbeiten*, 43, 135-147.

Besler, H., 1976: Wasserüberformte Dünen als Gelei' in der Landschaftgenese der Namib, *Baseler Afrika Bibliographien*, 15, 83-106.

Besler, H., 1977: Untersuchungen in der Dünen-Namib (Südwestafrika), *Journal of the South West African Scientific Society*, 31, 33-64.

Besler, H., 1979: Salinitätsmessungen an Sanden als Hilfsmittel zur Rekonstruktion fossiler Gewässernetze in ariden Räumen (nach Untersuchungen im Namib Erg), *Zeitschrift für Geomorphologie* , 23, 192-198.

Besler, H., 1980: Die Dünen Namib: Entstehung und Dynamik eines Ergs, *Stuttgarter Geographische Studien*, 96, 1-208.

Besler, H., 1984: The development of the Namib dune field according to sedimentological and geomorphological evidence, in J.C.Vogel, (ed.), *Late Cainozoic Palaeoclimates of the Southern Hemisphere*, Balkema, Rotterdam, 445-453.

Besler, H., Marker, M.E., Ollier, C.D. and Selby, M.J., 1977: Geomorphological research in the Namib, *Namib Bulletin, Supplement to the Bulletin of the Transvaal Museum*, October, 2, 6-8.

Besler, H. and Marker, M.E., 1979: Namib sandstone: a distinct lithological unit, *Transactions of the Geological Society of South Africa*, 82, 155-160.

Bigarella, J.J., 1972: Eolian environments: their characteristics, recognition and importance, *Special Publication of the Society of Economic Palaeontologists and Mineralogists*, 16, 12-62.

Blatt, H.G., Middleton, G.V. and Murray, R., 1980: *Origins of Sedimentary Rocks*, Prentice Hall, Englewood Cliffs.

Blümel, W.D., 1982: Calcretes in Namibia and SE-Spain, relations to substratum, soil formation and geomorphic factors, in D.H.Yaalon (ed.) *Aridic Soils and Geomorphic Processes*, Catena Supplement, 1, 67 - 82, Braunschweig.

Bull, W.B., 1977: The alluvial fan environment, *Progress in Physical Geography*, 1, 222-270.

Capot-Rey, R., 1970: Remarques sur les ergs du Sahara, *Annales de Geographie*, 79, 2-19.

Carrington, A.J. and Kensley, B.F., 1969: Pleistocene molluscs from the Namaqualand coast, *Annals of the South African Museum*, 52, 189-223.

Coetzee, J.A., 1978a: Climatic and biological changes in south-western Africa during the late Cainozoic, *Palaeoecology of Africa*, 10, 13-29.

Coetzee, J.A., 1978b: Late Cainozoic palaeoenvironments of southern Africa, in E.M. Van Zinderen Bakker (ed.), *Antarctic Glacial History and World Palaeoenvironments*, Balkema, Rotterdam, 115-127.

Coetzee, J.A., 1980: Tertiary environmental changes along the south western African coast, *Palaeontologica Africana*, 23, 197-203.

Cooke, R.U. and Warren, A., 1973: *Geomorphology in Deserts*, Batsford, London.

Corvinus, G. and Hendey, Q.B., 1978: A new Miocene vertebrate locality at Arrisdrift in South West Africa (Namibia), *Neues Jahrbuch für Geologie und Palaeontologie, Monatshefte*, 193-205.

Denton, G.H., 1985: Did the Antarctic ice sheet influence late Cainozoic climate and evolution in the southern hemisphere?, *South African Journal of Science*, 81, 224-229.

Dingle, R.V. and Scruton, R.A., 1974: Continental breakup and the development of post-Palaeozoic sedimentary basins around Southern Africa, *Bulletin of the Geological Society of America*, 85, 1467-1474.

Endrödy-Younga, S., 1978: Coleoptera, in M.J.Werger (ed.), *Biogeography and Ecology of Southern Africa*, Junk, The Hague, 797-821.

Endrödy-Younga, S., 1982: Dispersion and translocation of dune specialist tenebrionids in the Namib area, *Cimbebasia*, 5, 257-271.

Fenwick, G.A., 1989: Grain size and easterly wind influences on linear dunes of the central Namib desert, *ABSTRACTS*, Conference of the South African Society for Geography, Pretoria, July.

Fenwick, G.A., 1990: Grain size and easterly wind influences on linear dunes of the central Namib desert, *Zeitschrift für Geomorphologie - in preparation*

Fryberger, S.G., Ahlbrandt, T.S. and Andrews, S., 1979: Origin, sedimentary features, and significance of low-angle eolian 'sand sheet' deposits, Great Sand Dunes National Monument and vicinity, Colorado, *Journal of Sedimentary Petrology*, 49, 733-746.

Gevers, T.W., 1936: The morphology of western Damaraland and the adjoining Namib desert of South West Africa, *South African Geographical Journal*, 19, 61-78.

Gile, L.H., Peterson, F.F. and Grossman, R.B., 1966: Morphological and genetic sequences of carbonate accumulation in desert soils, *Soil Sciences*, 101, 347-360.

Glennie, K.W. and Evamy, B.D., 1968: Dikaka: Plants and plant-root structures associated with aeolian sand, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 4, 77-87.

Goudie, A.S., 1972: Climate, weathering crust formation, dunes and fluvial features of the central Namib desert, near Gobabeb, South West Africa, *Madoqua*, 11, 15-31.

Goudie, A., 1973: *Duricrusts in Tropical and Subtropical Landscapes*, Oxford, Oxford.

Goudie, A. and Wilkinson, J., 1977: *The Warm Desert Environment*, Cambridge, Cambridge.

Greenman, I., 1969: The Elizabeth Bay Formation, Lüderitz and its bearing on the genesis of dolomite, *Transactions of the Geological Society of South Africa*, 72, 115-121.

Hallam, A., 1987: End-Cretaceous mass extinction event; argument for terrestrial causation, *Science*, 239, 1237-1242.

Harmse, J.T., 1980: Die nooordwaartse begrensing van die Sentrale Namib duinsee langs die Benede-Kuiseb, Unpublished MA thesis, University of Stellenbosch.

Harwood, D.M., 1985: Late Neogene climatic fluctuations in the southern high-latitudes: implications of a warm Pliocene and deglaciated Antarctic continent, *South African Journal of Science*, 81, 239-241.

Haughton, S.H., 1931: The late Tertiary and recent deposits of the west coast of South Africa, *Transactions of the Geological Society of South Africa*, 34, 19-57.

Hendey, Q.B., 1978: Preliminary report on the Miocene vertebrates from Arrisdrift, South West Africa, *Annals of the South African Museum*, 76, 1-41.

Hut, P., Alvarez, W., Elder, W.P., Hansen, T., Kauffman, E.G., Keller, G., Shoemaker, E.M. and Weissman, P., 1987: Comet showers as a cause of mass extinctions, *Nature*, 329, 118-126.

Kaiser, E., 1926: *Die Diamanten Wüste Südwestafrikas*, Dietrich Reimer, Berlin.

Kennett, J.P. and Thunell, R.C., 1975: Global increase in Quaternary explosive volcanism, *Science*, 187, 497-503.

King, L.C., 1951 (2nd Edition): *South African Scenery*, Oliver and Boyd, Edinburgh.

King, L.C., 1953: Canons of landscape evolution, *Bulletin of the Geological Society of America*, 64, 721-752.

King, L.C. 1962: *The Morphology of the Earth*, Oliver and Boyd, Edinburgh.

Koch, C., 1961: Some aspects of the abundance of life in the vegetationless sand of the Namib desert dunes, *Journal of the South West African Scientific Society*, 15, 8-34.

Koch, C., 1962: The Tenebrionidae of southern Africa XXXI, comprehensive notes on the Tenebrionid fauna of the Namib desert, *Annals of the Transvaal Museum*, 24, 61-106.

Korn, H. and Martin, H., 1957: The Pleistocene in South West Africa, *Proceedings of the 3rd Pan African Congress on Prehistory*, 14-22.

Lancaster, N., 1984a: Late Cainozoic fluvial deposits of the Tsondab valley, central Namib desert, *Madoqua*, 13, 257-269.

Lancaster, N., 1984b: Palaeoenvironments in the Tsondab valley, Central Namib desert, *Palaeoecology of Africa*, 16, 411-420.

Lancaster, N., 1984c: Aridity in southern Africa: age, origins and expression in landforms and sediments, in J.C. Vogel, (ed.), *Late Cainozoic Palaeoclimates of the Southern Hemisphere*, Balkema, Rotterdam, 433- 444.

Lancaster, N., 1989: *The Namib Sand Sea*, Balkema, Rotterdam.

Lancaster, N. and Ollier, C.D., 1983: Sources of sand for the Namib sand sea, *Zeitschrift für Geomorphologie, Supplementband*, 45, 71-83.

Logan, R.F., 1960: *The Central Namib Desert, South West Africa*, National Research Council, Washington, D.C., Publication number 758.

Mabbutt, J.A., 1952: The evolution of the middle Ugab valley, Damaraland, South West Africa, *Transactions of the Royal Society of South Africa*, 33, 334-366.

Mabbut, J.A., 1977: *Desert Landforms*, Australian National University Press, Canberra.

Marker, M.E., 1977a: A long term geomorphic event in the Namib desert, S.W.A., *Area*, 9, 209-213.

Marker, M.E., 1977b: Aspects of the geomorphology of the Kuiseb river, South West Africa, *Madoqua*, 10, 199-206.

Marker M.E., 1979: Relict fluvial terrace on the Tsondab Flats, Namibia, *Journal of Arid Environments*, 2, 113-117.

Marker, M.E., 1982: Aspects of Namib geomorphology: a doline karst, *Palaeoecology of Africa*, 15, 187-189.

Marker, M.E. and Müller, D., 1978: Relict vlei silts of the middle Kuiseb valley, South West Africa, *Madoqua*, 11, 151-162.

Martin, H., 1950: Südwestafrika, *Geologische Rundschau*, 38, 6-14.

Martin, H., 1957: *The Sheltering Desert*, William Kimber, London.

Martin, H., 1961: Abriss der geologischen Geschichte Südwestafrikas, *Journal of the South West African Scientific Society*, 15, 57-66.

Martin, H., 1973: Paleozoic, Mesozoic and Cenozoic deposits on the coast of South West Africa, in *Sedimentary Basins of the African Coast*, Part 2, South and East Coasts.

Martin, H., 1975: Structural and palaeogeographical evidence for an upper Palaeozoic sea between Southern Africa and South America, Proceedings paper, IUGS 3rd Gondwana symposium, Canberra, 37-51

McKee, E.D. 1982: Sedimentary structures in dunes of the Namib desert, South West Africa, *Geology Society of America*, Special paper 188, 1-64.

Mclain, D.R., Brainhard, R.D. and Norton, J.G., 1985: Anomalous warm events in eastern boundary current systems, *CalCOFI report 26*, 51-64.

Miller, R. McG. and Seely, M.K., 1976: Fluvio-marine deposits south-east of Swakopmund, South West Africa, *Madoqua*, 9, 23-26.

Miller, K.G., and Fairbanks, R.G., 1985: Cainozoic 18/O record of climate and sea level, *South African Journal of Science*, 81, 248-249.

Meigs, P., 1966: Geography of coastal deserts, *Unesco Arid Zone Research*, 28, 11-40.

Netterberg, F., 1969a: The Geology and Engineering Properties of South African Calcretes, unpublished PhD thesis, University of the Witwatersrand, Johannesburg.

Netterberg, F., 1969b: Ages of calcretes in South Africa, *South African Archaeological Bulletin*, 29, 83-88.

Netterberg, F., 1969c: The interpretation of some basic calcrete types, *South African Archaeological Bulletin*, 24, 117-122.

Netterberg, F., 1980: Geology of South African calcretes I. Terminology, description, macrofeatures and classification, *Transactions of the Geological Society of South Africa*, 83, 255-283.

Netterberg, F., 1982: Calcrete formation, classification, age and distribution, Geological Society of South Africa, Winterschool, 7.

Ollier, C.D. 1977: Outline geological and geomorphic history of the central Namib Desert, *Madoqua*, 10, 202-212.

Ollier, C.D., 1978: Inselbergs of the Namib desert - processes and history, *Zeitschrift für Geomorphologie*, 31, 161-176.

Ollier, C.D. and Seely, M.K., 1977: Patterned ground near Gobabeb, central Namib desert, *Madoqua*, 10, 213-214.

Partridge, T.C., 1985a: Tertiary to recent coastal deposits, in A.B.A. Brink (ed.), *Engineering Geology of Southern Africa*. Building Publications, Pretoria, 4, 57-90.

Partridge, T.C., 1985b: The palaeoclimatic significance of Cainozoic terrestrial stratigraphic and tectonic evidence from Southern Africa: a review, *South African Journal of Science*, 81, 245-247.

Partridge, T.C., 1990 (in press): Cainozoic environmental changes in southern Africa, *South African Journal of Science*.

Partridge, T.C. and Maud, R.R., 1987: Geomorphic evolution of southern Africa since the Mesozoic, *South African Journal of Geology*, 90, 179-205.

Partridge, T.C. and Maud, R.R., 1988: The geomorphic evolution of southern Africa: a comparative review, in G.F. Dardis and B.P. Moon (eds), *Geomorphological Studies in Southern Africa*, Balkema, Rotterdam, 5-16.

Partridge T.C. and Maud R.R., 1989: The end-Cretaceous event: new evidence from the southern hemisphere, *South African Journal of Science*, 85, 428-430.

Reading, H.G., 1978 (second edition 1986): *Sedimentary Environments and Facies*, Blackwell Scientific, Oxford.

Reeves, C.C., 1970: Origin, classification and geologic history of caliche on the southern High Plains, Texas and eastern New Mexico, *Journal of Geology*, 78, 187-199.

Reinek, H.E. and Singh, I.B., 1973: *Depositional Sedimentary Environments*, Springer, New York.

Rogers, J., 1977: Sedimentation on the continental margins off the Orange River and the Namib desert, *Joint Geological Survey/University of Cape Town Marine Geoscience Group Bulletin*, 7.

Marker, M.E., 1977a: A long term geomorphic event in the Namib desert, S.W.A., *Area*, 9, 209-213.

Marker, M.E., 1977b: Aspects of the geomorphology of the Kuiseb river, South West Africa, *Madoqua*, 10, 199-206.

Marker M.E., 1979: Relict fluvial terrace on the Tsondab Flats, Namibia, *Journal of Arid Environments*, 2, 113-117.

Marker, M.E., 1982: Aspects of Namib geomorphology: a doline karst, *Palaeoecology of Africa*, 15, 187-189.

Marker, M.E. and Müller, D., 1978: Relict vlei silts of the middle Kuiseb valley, South West Africa, *Madoqua*, 11, 151-162.

Martin, H., 1950: Südwestafrika, *Geologische Rundschau*, 38, 6-14.

Martin, H., 1957: *The Sheltering Desert*, William Kimber, London.

Martin, H., 1961: Abriss der geologischen Geschichte Südwestafrikas, *Journal of the South West African Scientific Society*, 15, 57-66.

Martin, H., 1973: Paleozoic, Mesozoic and Cenozoic deposits on the coast of South West Africa, in *Sedimentary Basins of the African Coast*, Part 2, South and East Coasts.

Martin, H., 1975: Structural and palaeogeographical evidence for an upper Palaeozoic sea between Southern Africa and South America, Proceedings paper, IUGS 3rd Gondwana symposium, Canberra, 37-51

McKee, E.D. 1982: Sedimentary structures in dunes of the Namib desert, South West Africa, *Geology Society of America*, Special paper 188, 1-64.

Mclain, D.R., Brainhard, R.D. and Norton, J.G., 1985: Anomalous warm events in eastern boundary current systems, *CalCOFI report 26*, 51-64.

Miller, R. McG. and Seely, M.K., 1976: Fluvio-marine deposits south-east of Swakopmund, South West Africa, *Madoqua*, 9, 23-26.

Miller, K.G., and Fairbanks, R.G., 1985: Cainozoic 18/O record of climate and sea level, *South African Journal of Science*, 81, 248-249.

Meigs, P., 1966: Geography of coastal deserts, *Unesco Arid Zone Research*, 28, 11-40.

Netterberg, F., 1969a: The Geology and Engineering Properties of South African Calcretes, unpublished PhD thesis, University of the Witwatersrand, Johannesburg.

Netterberg, F., 1969b: Ages of calcretes in South Africa, *South African Archaeological Bulletin*, 29, 83-85.

Netterberg, F., 1969c: The interpretation of some basic calcrete types, *South African Archaeological Bulletin*, 24, 117-122.

Netterberg, F., 1980: Geology of South African calcretes I. Terminology, description, macrofeatures and classification, *Transactions of the Geological Society of South Africa*, 83, 255-283.

Netterberg, F., 1982: Calcrete formation, classification, age and distribution, Geological Society of South Africa, Winterschool, 7.

Ollier, C.D. 1977: Outline geological and geomorphic history of the central Namib Desert, *Madoqua*, 10, 202-212.

Ollier, C.D., 1978: Inselbergs of the Namib desert - processes and history, *Zeitschrift für Geomorphologie*, 31, 161-176.

Ollier, C.D. and Seely, M.K., 1977: Patterned ground near Gobabeb, central Namib desert, *Madoqua*, 10, 213-214.

Partridge, T.C., 1985a: Tertiary to recent coastal deposits, in A.B.A. Brink (ed.), *Engineering Geology of Southern Africa*, Building Publications, Pretoria, 4, 57-90.

Partridge, T.C., 1985b: The palaeoclimatic significance of Cainozoic terrestrial stratigraphic and tectonic evidence from Southern Africa: a review, *South African Journal of Science*, 81, 245-247.

Partridge, T.C., 1990 (in press): Cainozoic environmental changes in southern Africa, *South African Journal of Science*.

Partridge, T.C. and Maud, R.R., 1987: Geomorphic evolution of southern Africa since the Mesozoic, *South African Journal of Geology*, 90, 179-205.

Partridge, T.C. and Maud, R.R., 1988: The geomorphic evolution of southern Africa: a comparative review, in G.F. Dardis and B.P. Moon (eds), *Geomorphological Studies in Southern Africa*, Balkema, Rotterdam, 5-16.

Partridge T.C. and Maud R.R., 1989: The end-Cretaceous event: new evidence from the southern hemisphere, *South African Journal of Science*, 85, 428-430.

Reading, H.G., 1978 (second edition 1986): *Sedimentary Environments and Facies*, Blackwell Scientific, Oxford.

Reeves, C.C., 1970: Origin, classification and geologic history of caliche on the southern High Plains, Texas and eastern New Mexico, *Journal of Geology*, 78, 187-199.

Reinek, H.E. and Singh, I.B., 1973: *Depositional Sedimentary Environments*, Springer, New York.

Rogers, J., 1977: Sedimentation on the continental margins off the Orange River and the Namib desert, *Joint Geological Survey/University of Cape Town Marine Geoscience Group Bulletin*, 7.

Rohdenburg, H. and Sabelberg, V., 1969: "Kalkkrusten" und ihr klimatischer Aussagewert: Neue Beobachtungen aus Spanien und N-Afrika, *Göttinger Bodenkundliche Berichte*, 7, 3-26.

Rohdenburg, H. and Sabelberg, V., 1973: Quartaere Klimazyklen im Westlichen Mediterran-Gebiet und ihre Auswirkungen auf die Relief und Bodenentwicklung, *Catena*, 71-180.

Rubin, D.M., and Hunter, R.E., 1985: Why deposits of longitudinal dunes are rarely recognised in the geologic record, *Sedimentology*, 32, 147-157.

Rust, U. and Wieneke, F., 1974: Studies on gramadulla formation in the middle part of the Kuiseb river, South West Africa, *Madoqua*, 3, 5-15.

Rust, U. and Wieneke, F., 1976: Geomorphologie der küstennahen zentralen Namib (Südwestafrika), *Münchener Geographische Abhandlungen*, 19.

Rust, U. and Wieneke, F., 1980: A reinvestigation of some aspects of the evolution of the Kuiseb River valley upstream of Gobabeb, South West Africa, *Madoqua*, 12, 163-173.

Sabelberg, V. and Rohdenburg, H., 1975: Stratigraphische Stellung und klimatisch-geoökologischer Aussagewert der Kalkkrusten in Spanien und Marokko, *Types de Croutes cacaires et leur re'partition re'gionale*, Strasbourg 9-11 Jan, 120-128.

Scholz, H., 1972: The soils of the central Namib desert with special consideration of the soils in the vicinity of Gobabeb, *Madoqua*, 1, 33-51.

Schulze, B.R., 1969: The climate of Gobabeb, *Scientific Papers of the Namib Desert Research Station*, 38, 5-12.

Seely, M.K., 1978: The Namib dune desert: an unusual ecosystem, *Journal of Arid Environments*, 1, 117-128.

Seely, M.K., 1984: The Namib's place among deserts of the world, *South African Journal of Science*, 80, 155-158.

Seely, M.K. and Louw, G.N., 1980: First approximation of the effects of rainfall on the ecology and energetics of a Namib desert dune ecosystem, *Journal of Arid Environments*, 3, 25-54.

Seely, M.K. and Mitchell, D., 1986: Termite casts in Tsondab sandstone?, *Palaeoecology of Africa*, 17, 109-112.

Seely, M.K. and Ward, J.D., 1988: The Namib desert, in I.A.W. Macdonald and R.J.M. Crawford (eds), *Long-Term Data Series Relating to Southern Africa's Renewable Natural Resources*, South African National Scientific Programmes Report, 157, 268-279.

Selby, M.J., 1976: Some thoughts on the geomorphology of the central Namib desert, *Bulletin of the Desert Ecological Research Unit*, 1, 5-6.

Selby, M.J. 1977: Bornhardts of the Namib Desert, *Zeitschrift für Geomorphologie*, 21, 1-13.

Selley, 1976 (second ed. 1982): *Introduction to Sedimentology*, Academic Press, London.

Shackleton, N.J. and Kennett, J.P., 1975: Palaeotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analyses in DSDP sites 277, 279 and 281, in J.P.Kennet, R.E.Houtz *Et al*, (eds), *Initial Reports of the Deep Sea Drilling Project*, 29, 743-755.

Shannon, L.V., 1985: The Benguela ecosystem. 1. Evolution of the Benguela, physical features and processes, in M.Barnes (ed.), *Oceanography and Marine Biology, An Annual Review*, 23, University Press, Aberdeen, 105-182.

Siegfried, W.R., 1989: in L.V.Shannon, M.K.Seely and J.D.Ward, (convenors), Proceedings of the Namib-Benguela Interactions Workshop, Gobabeb, SWA Namibia, Occasional paper 41, Ecosystem programmes, FRD, 29.

Siesser, W.G., 1978: Aridification in the Namib: evidence from ocean cores, in E.M. Van Zinderen Bakker, (ed.) *Antarctic Glacial History and World Palaeoenvironments*, Balkema, Rotterdam, 105-113.

Siesser, W.G., 1980: Late Miocene origin of the Benguela upwelling system off northern Namibia, *Science*, 208, 283-285.

Simpson, E.S.W., 1977: Evolution of the south Atlantic, Alex C. du Toit memorial lecture 15, 1-15, *Geological Society of South Africa*, Annex., LXXX.

Smith, A.G. and Briden, J.C., 1982: *Mesozoic and Cenozoic Palaeocontinental Maps*, Cambridge, Cambridge.

Smithers, R.H.N., 1983: The Mammals of the Southern African Subregion, University of Pretoria, Pretoria.

South African Committee for Stratigraphy (SACS), 1980: Stratigraphy of South Africa, Part 1., (Compiled by L.E.Kent), Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophutatswana, Transkei and Venda, *Handbook of the Geological Survey of South Africa*, 8.

Soares Carvalho, G., 1961: Geologia do deserto de Mocamedes (Angola) *Memorias, Junta de Investigacoes do Ultramar*, Ser. 2, 26.

Stapff, F.M., 1887: Karte des unteren !Kuisebthales, *A.Petermanns Mitteilungen aus J. Perthes Geographischer Anstalt, Gotha* 33, 202-214.

Stengel, H.W., 1964: Die Riviere der Namib und ihr Zulauf zum Atlantik, Teil 1: Kuiseb und Swakop, *Scientific papers, Namib Desert Research Station*, 22.

Stengel, H.W., 1970: Die riviere van die Namib met hulle toeloepe na die Atlantiese oseaan, Derde Deel: Tsondab, Tsams en Tsauchab, Unpublished report, Department of Water Affairs, S.W.A. Branch.

Tankard, A.J., Jackson, M.P.A., Eriksson, K.A., Hobday., D.K., Hunter, D.R. and Minter, W.E.L., 1982: *Crustal Evolution of Southern Africa, 3.8 Billion Years of Earth History*, Springer, New York.

Tankard, A.J. and Rogers, J., 1978: Late Cenozoic palaeoenvironments on the west coast of southern Africa, *Journal of Biogeography*, 5, 319-337.

Tyson, P.D., 1986: *Climatic Change and Variability over Southern Africa*, Oxford, Cape Town.

Van Zinderen Bakker, E.M., 1975: The origin and palaeoenvironment of the Namib desert biome, *Journal of Biogeography*, 2, 65-73.

Van Zinderen Bakker, E.M., 1984: Aridity along the Namibian coast, *Palaeoecology of Africa*, 16, 149-160.

Van Zijl, J.S.V., 1970: Kuisebrivier Delta - resultate van seismiese refraksie opnames, Unpublished map, CSIR.

Vogel, J.C., 1982: The age of the Kuiseb river silt terrace at Homeb, *Palaeoecology of Africa*, 15, 201-209.

Vogt, P.E., 1972: Evidence for global synchronism in mantle plume convection and possible significance for geology, *Nature*, 240, 338-342.

Walker, R.G. and Middleton, G.V., 1977: Facies models 9: eolian sands, *Geoscience Canada*, 4, 182-190.

Walton, K., 1969: *The Arid Zones*, Hutchinson University Library, London.

Ward, J.D., 1982: Aspects of a suite of Quaternary conglomeratic sediments in the Kuiseb valley, Namibia, *Palaeoecology of Africa*, 15, 211-216.

Ward, J.D., 1984a: Aspects of the Cenozoic geology of the Kuiseb valley, central Namib desert, Unpublished PhD thesis, University of Natal, Pietermaritzburg.

Ward, J.D., 1984b: A reappraisal of the Cenozoic stratigraphy in the Kuiseb valley of the central Namib desert, in J.C. Vogel, (ed.), *Late Cainozoic Palaeoclimates of the Southern Hemisphere*, Balkema, Rotterdam, 455-463.

Ward, J.D., 1987: The Cenozoic succession in the Kuiseb valley, Namib desert, *Memoir of the Geological Survey*, South West Africa/Namibia, 9.

Ward, J.D., 1988a: Aeolian, fluvial and pan(playa) facies of the Tertiary Tsondab sandstone formation in the central Namib desert, Namibia, *Sedimentary Geology*, 55, 143-162.

Ward, J.D., 1988b: The central Namib desert, in H.R. Beckendahl, B.P. Moon and G.F. Dardis, (eds), *Southern African Landscapes: A Geomorphological Field Guide*, University of Transkei, Umtata, 117-135.

Ward, J.D., Seely, M.K. and Lancaster, N., 1983: On the antiquity of the Namib, *South African Journal of Science*, 79, 175-183.

Watson, A., 1980: Vegetation polygons in the central Namib desert near Gobabeb, *Madoqua*, 11, 315-325.

Watts, N.L., 1977: Pseudo-anticlines and other structures in some calcretes in Botswana and South Africa, *Earth Surface Procceses*, 2, 63-74.

Webb, P.N., *et al*, 1984: Cenozoic marine sedimentation on the east Antarctic craton, *Geology*, 12, 287-291.

Werner, D., 1971: Böden mit Kalkanreicherungshorizonten in NW-Argentinien, *Göttinger Bödenkundliche Berichte*, 19, 167-181.

Wilkinson, M.J., 1987: A late Cenozoic geomorphic history of the Tumas drainage basin in the Central Namib desert, Unpublished PhD. thesis, University of Chicago.

Wilkinson, M.J., 1988a: Tertiary events in the Tumas river basin, central Namib desert: geology and geomorphology of the Naarip plain, in, H.R. Beckendahl, B.P.Moon and G.F.Dardis (eds) *Southern African Landscapes: A Geomorphological Field Guide*, University of Transkei, Umtata, 137-165.

Wilkinson, M.J., 1988b: Late Cenozoic environments of the central Namib desert: the case of the Tumas river, Research paper, Department of Geography, University of Chicago, 205.

Wilkinson, M.J., 1988c: The Tumas sandstone formation of the central Namib desert - palaeoenvironmental implications, *Palaeoecology of Africa*, 19, 139 - 150.

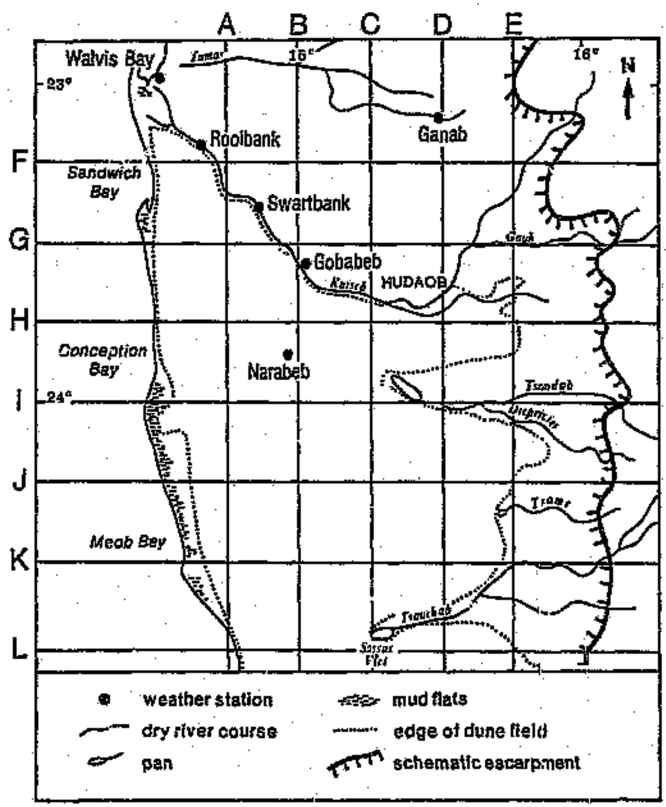
Wilmer, H.C., 1893: The relation of the sand dune formation on the south west coast of Africa to the local wind currents, *Transactions of the South African Philosophical Society*, 5, 326-329.

Yaalon, D.H. and Ward, J.D., 1982: Observations on calcrete and recent calcic horizons in relation to landforms, central Namib desert, *Palaeoecology of Africa*, 15, 183-186.

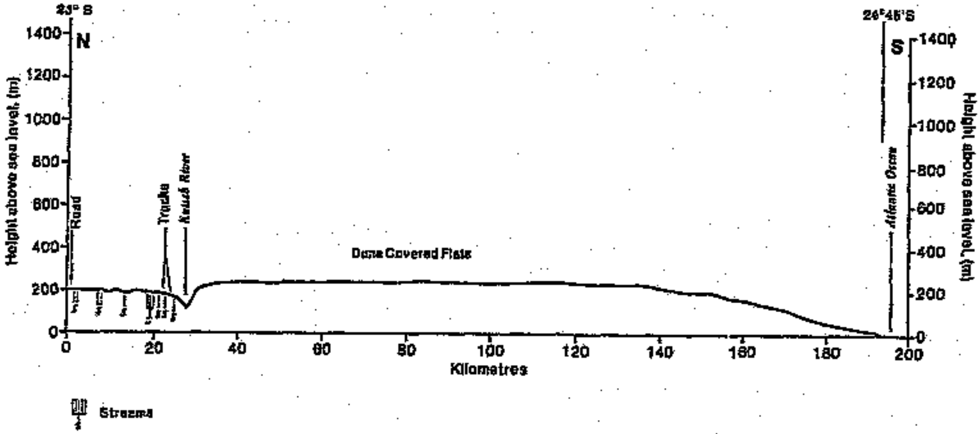
Appendix I

Cross sections north to south

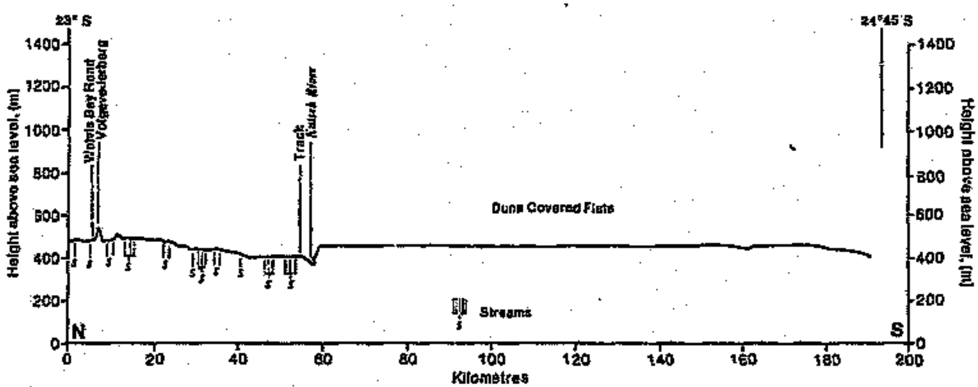
1. Base orientational map for cross sections.
2. Cross section A. 14°45'E.
3. Cross section B. 15°E.
4. Cross section C. 15°15'E.
5. Cross section D. 15°30'E.
6. Cross section E. 15°45'E.



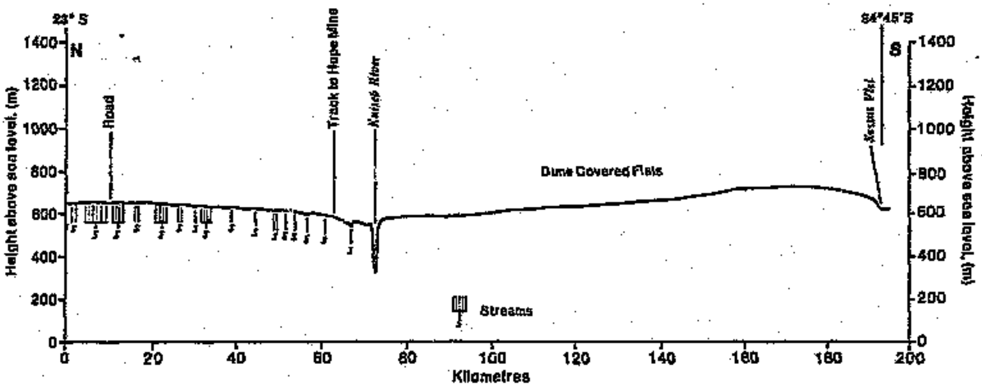
Appendix 1.1: Base orientational map for cross sections



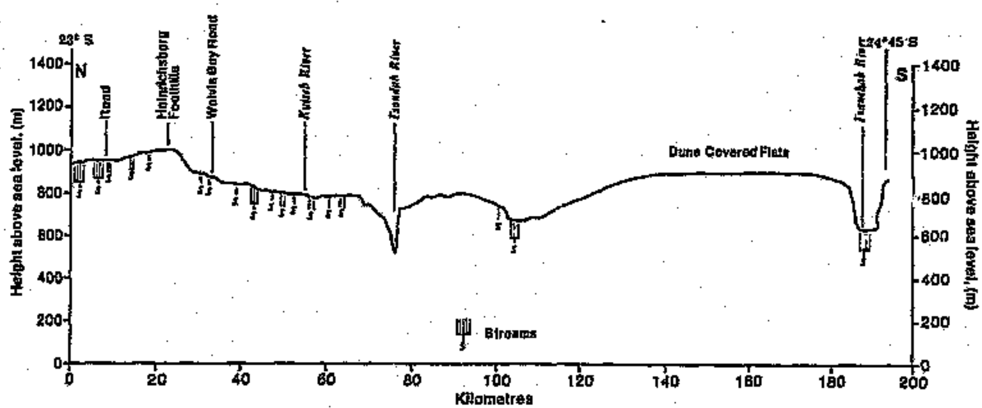
Appendix 1.2: Cross section A. 14°45' E.



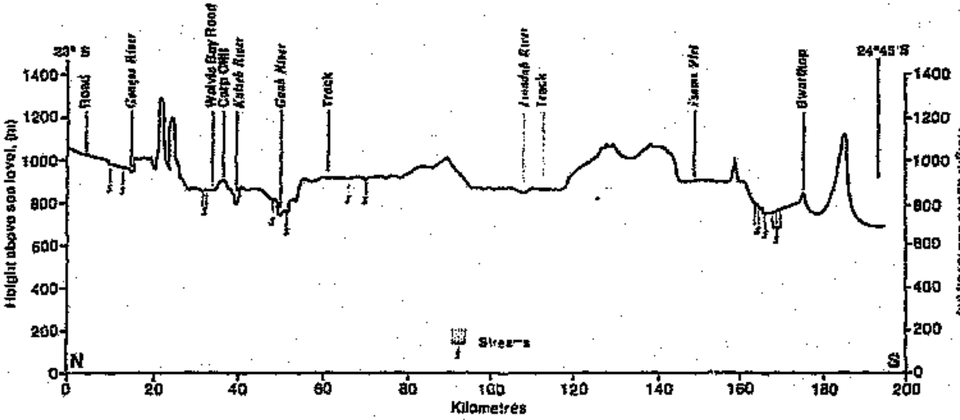
Appendix 1.3: Cross section B. 15° E.



Appendix 1.4: Cross section C. 15°15' E.



Appendix 1.5: Cross section D. 15°30' E.

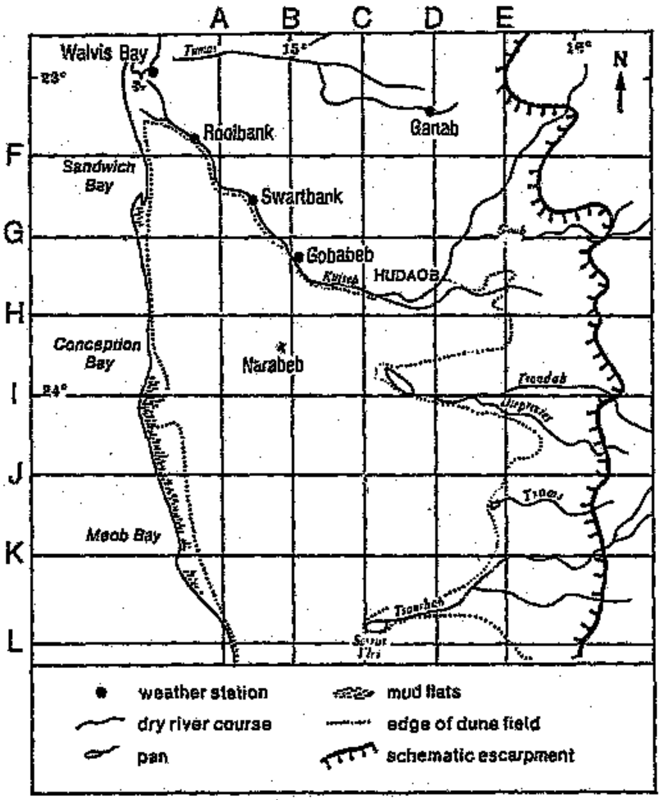


Appendix 1.6: Cross section E. 15°45' E.

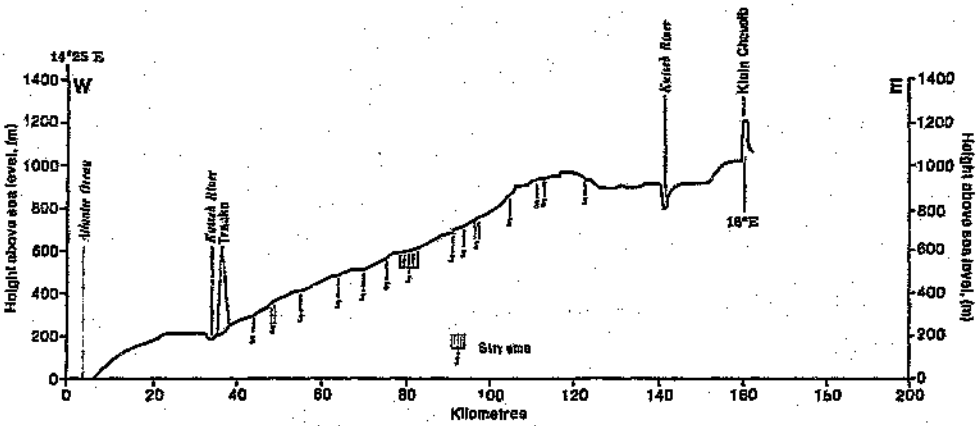
Appendix 2

Cross sections east to west

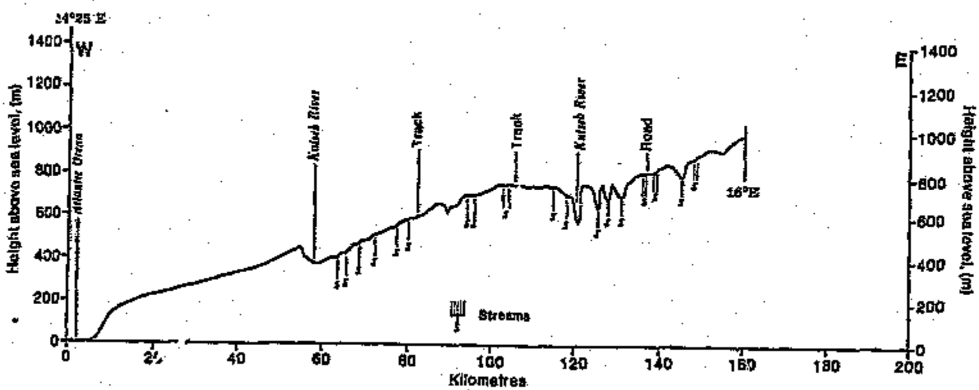
1. Base orientational map for cross sections.
2. Cross section F. 23°15'S.
3. Cross section G. 23°30'S.
4. Cross section H. 23°45'S.
5. Cross section I. 24°S.
6. Cross section J. 24°15'S.
7. Cross section K. 24°30'S.
8. Cross section L. 24°45'S.



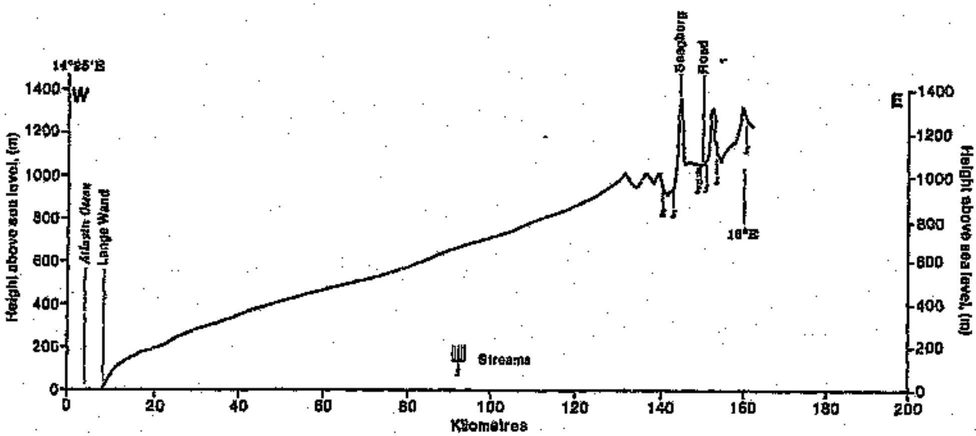
Appendix 2.1: Base orientational map for cross sections



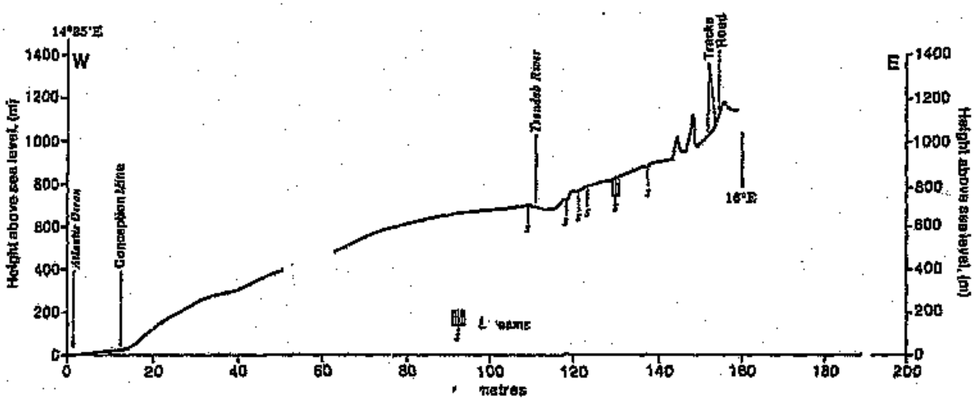
Appendix 2.2: Cross section F. 23°15' S.



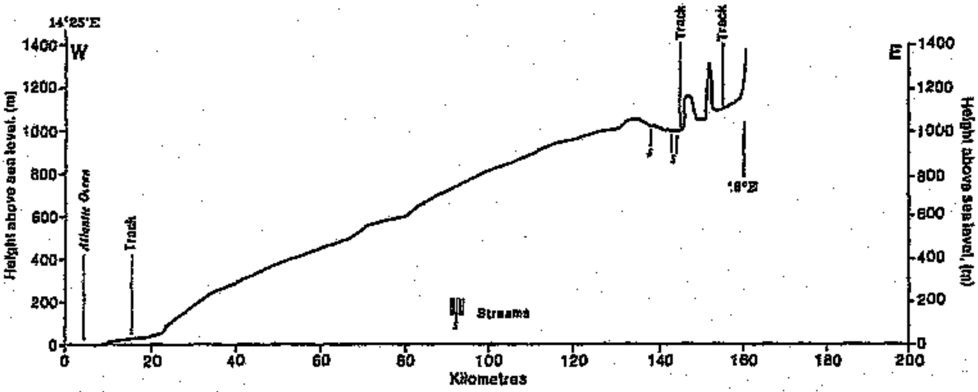
Appendix 2.3: Cross section G. 23°30' E.



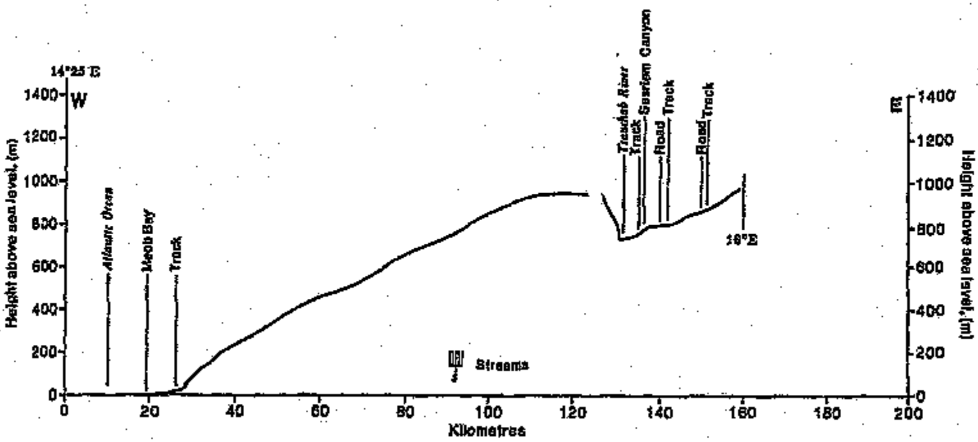
Appendix 2.4: Cross section H. 23°45' S.



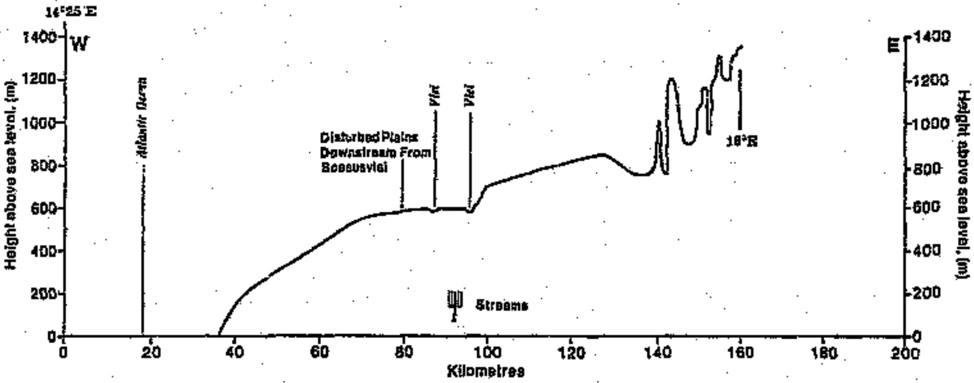
Appendix 2.5: Cross section I. 24° S.



Appendix 2.6: Cross section J. 24°15' S.



Appendix 2.7: Cross section K. 24°30' S



Appendix 2.8: Cross section L. 24°45' S.

Appendix 3

Recent Satellite Images Available for the Central Namib Desert.

1. WRS 179-076 from 20th May 1984 to 17th August 1987.
2. WRS 179-076 from 18th October 1987 to 7th October 1989.
3. WRS 179-077 from 4th May 1984 to 1st September 1987.
4. WRS 179-077 from 17th September 1987 to 7th October 1989.

SATELLITE APPLICATIONS CENTRE ,P.O.BOX 395 , PRETORIA ,0001 REPUBLIC OF SOUTH AFRICA

LANDSAT 5 MSS SCENES AVAILABLE FOR WRS: 179-076 WITH MAX. CLOUDCOVER OF 50% FOR THE TIME PERIOD 24-MAR-84 TO 12-OCT-87.

WRS TRK-FRM	SCENE ID	SOURCE No.	SOURCE TYPE	BAND QUALITY 12345678	CLOUD COVER	DATE	SCENE CENTRE LAT.	SCENE CENTRE LONG.	PRODUCT TAPE-No.	FILM No.	STD PRODUCTS 12345678PN	IAS PRODUCTS 12345678PN	IAS PROCESS
179-076	50080-08215	L84051971	[illegible]	[illegible]	4156	840520	S23.14	E015.26					
179-076	50096-08251	L84060471	[illegible]	[illegible]	0000	840605	S23.14	E015.25					
179-076	50112-08253	L84061872	[illegible]	[illegible]	1010	840621	S23.14	E015.24					
179-076	50128-08254	L84070772	[illegible]	[illegible]	4040	840707	S23.13	E015.25					
179-076	50144-08260	L84072271	[illegible]	[illegible]	0000	840724	S23.14	E015.21					
179-076	50176-08271	L84082172	[illegible]	[illegible]	4020	840824	S23.14	E015.27					
179-076	50192-08271	L84090772	[illegible]	[illegible]	1010	840909	S23.14	E015.30					
179-076	50208-08271	L84092372	[illegible]	[illegible]	1111	840925	S23.14	E015.34					
179-076	50224-08271	L84100972	[illegible]	[illegible]	2020	841011	S23.14	E015.19					
179-076	50240-08271	L84102671	[illegible]	[illegible]	0120	841027	S23.14	E015.25					
179-076	50256-08270	L84111171	[illegible]	[illegible]	3010	841112	S23.14	E015.32					
179-076	50272-08270	L84112771	[illegible]	[illegible]	1070	841128	S23.14	E015.34					
179-076	50288-08271	L84121371	[illegible]	[illegible]	0010	841214	S23.14	E015.33					
179-076	50304-08272	L84122772	[illegible]	[illegible]	7350	841230	S23.14	E015.31					
179-076	50320-08272	L85011571	[illegible]	[illegible]	6091	850115	S23.14	E015.30					
179-076	50336-08273	L85012871	[illegible]	[illegible]	6373	850131	S23.14	E015.28					
179-076	50352-08273	L85021372	[illegible]	[illegible]	1031	850216	S23.14	E015.29					
179-076	50368-08274	L85030171	[illegible]	[illegible]	1020	850304	S23.14	E015.30					
179-076	50384-08273	L85031672	[illegible]	[illegible]	2010	850320	S23.14	E015.30					
179-076	50400-08273	L85033172	[illegible]	[illegible]	2022	850405	S23.14	E015.30					
179-076	50416-08272	L85042071	[illegible]	[illegible]	0000	850421	S23.12	E015.32					
179-076	50432-08271	L85050472	[illegible]	[illegible]	1050	850507	S23.12	E015.33					
179-076	50448-08271	L85052172	[illegible]	[illegible]	2020	850523	S23.12	E015.31					
179-076	50464-08271	L85060672	[illegible]	[illegible]	0000	850608	S23.14	E015.24					
179-076	50480-08271	L85062172	[illegible]	[illegible]	2010	850624	S23.14	E015.27					
179-076	50496-08270	L85071971	[illegible]	[illegible]	3030	850710	S23.11	E015.22					
179-076	50512-08270	L85072472	[illegible]	[illegible]	1010	850726	S23.14	E015.27					
179-076	50528-08265	L85081171	[illegible]	[illegible]	0000	850811	S23.14	E015.27					
179-076	50560-08262	L85090872	[illegible]	[illegible]	0000	850912	S23.11	E015.25					
179-076	50576-08261	L85092771	[illegible]	[illegible]	5314	850928	S23.15	E015.19					
179-076	50592-08260	L85100371	[illegible]	[illegible]	3032	851014	S23.14	E015.20					
179-076	50608-08255	L85102772	[illegible]	[illegible]	0000	851030	S23.14	E015.20					
179-076	50624-08252	L85110772	[illegible]	[illegible]	2611	851115	S23.15	E015.20					
179-076	50704-08248	L86012372	[illegible]	[illegible]	3030	860203	S23.15	E015.20					
179-076	50816-08213	L86052671	[illegible]	[illegible]	2000	860526	S23.15	E015.23					
179-076	50864-08195	L86071972	[illegible]	[illegible]	5000	860713	S23.15	E015.26					
179-076	50880-08192	L86072771	[illegible]	[illegible]	0000	860729	S23.15	E015.27	2809	1886		U15	45 7
179-076/77	50880-08193	L86072771	[illegible]	[illegible]	0000	860729	S23.20	E015.13	1720	1645		U15	45 7
179-076	50896-08185	L86083172	[illegible]	[illegible]	0000	860814	S23.15	E015.29					
179-076	50912-08161	L86082671	[illegible]	[illegible]	0000	860830	S23.15	E015.31					
179-076	50928-08172	L86091471	[illegible]	[illegible]	0000	860915	S23.15	E015.31					
179-076	50976-08160	L86102821	[illegible]	[illegible]	2050	861102	S23.15	E015.27					
179-076	51008-08153	L86120271	[illegible]	[illegible]	3040	861204	S23.12	E015.20					
179-076	51040-08163	L861225	[illegible]	[illegible]	2010	870105	S23.12	E015.24					
179-076	51072-08173	L870131	[illegible]	[illegible]	2010	870206	S23.18	E015.26					
179-076	51104-08162	L870310	[illegible]	[illegible]	1010	870310	S23.11	E015.23					
179-076	51120-08193	L87032787	[illegible]	[illegible]	1310	870326	S23.12	E015.24					
179-076	51168-08206	L87051187	[illegible]	[illegible]	1010	870511	S23.11	E015.25					
179-076	51184-08212	L87052787	[illegible]	[illegible]	0000	870529	S23.10	E015.26					
179-076	51200-08214	L87061237	[illegible]	[illegible]	0000	870614	S23.14	E015.25					
179-076	51216-08220	L87062857	[illegible]	[illegible]	2010	870630	S23.11	E015.29					
179-076	51232-08222	L87071217	[illegible]	[illegible]	5201	870716	S23.12	E015.32					
179-076	51248-08224	L87072287	[illegible]	[illegible]	0000	870801	S23.12	E015.32					
179-076	51264-08231	L87081237	[illegible]	[illegible]	0000	870817	S23.12	E015.32					

Appendix 3.1: WRS 179-076 from 20th May 1984 to 17th August 1987.

SATELLITE APPLICATIONS CENTER ,P.O.BOX 395 , PRETORIA ,0001 REPUBLIC OF SOUTH AFRICA

LANDSAT 5(MSS) SCENES AVAILABLE FOR WRS: 179-076 WITH MAX. CLOUDCOVER OF 50% FOR THE TIME PERIOD 24-MAR-84 TO 12-DEC-89.

WRS PTH-ROW	SCENE ID	SOURCE No.	SOURCE TYPE	BAND QUALITY 12345678	CLOUD COVER	DATE	SCENE CENTRE LAT.	LONG.	PRODUCT TAPE-No.	FILM No.	BW PRODUCTS 12345678RGB	IAS PRODUCTS 12345678RGB	IAS PROCESS
179-076	[illegible]	[illegible]	HDDT	8888*	[illegible]	[illegible]	S23.10	E015.31					
179-076	51112-08242	[illegible]	HDDT	8888*	[illegible]	[illegible]	S23.14	E015.29		1979	81		
179-076	[illegible]	[illegible]	HDDT	8888*	3310	871028	S23.10	E015.31					
179-076	51144-08250	[illegible]	HDDT	8888*	4121	871105	S23.12	E015.31					
179-076	[illegible]	L8712057	HDDT	8888*	[illegible]	871207	S23.13	E015.31					
179-076	51192-08256	L8712157	HDDT	8888*	[illegible]	871223	S23.12	E015.31					
179-076	[illegible]	L8712297	HDDT	8888*	[illegible]	880108	S23.13	E015.33					
179-076	51424-08262	[illegible]	HDDT	8888*	[illegible]	[illegible]	S23.18	E015.30					
179-076	[illegible]	[illegible]	HDDT	8888*	[illegible]	[illegible]	S23.11	E015.27					
179-076	[illegible]	[illegible]	HDDT	8888*	[illegible]	[illegible]	S23.12	E015.27					
179-076	[illegible]	[illegible]	HDDT	8888*	[illegible]	[illegible]	S23.13	E015.27					
179-076	[illegible]	[illegible]	HDDT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
179-076	[illegible]	[illegible]	HDDT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
179-076	[illegible]	[illegible]	HDDT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		2115	11		H19 45 7
179-076	[illegible]	[illegible]	HDDT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
179-076	51616-08275	[illegible]	HDDT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
179-076	51680-08274	[illegible]	HDDT	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
179-076	51696-08274	[illegible]	HDDT	[illegible]	2020	[illegible]	[illegible]	[illegible]					
179-076	51744-08273	[illegible]	HDDT	8888*	2020	880709	S23.12	E015.28					
179-076	51760-08273	L8812297	HDDT	8888*	1110	881225	S23.11	E015.27					
179-076	51776-08277	L8901057	HDDT	8888*	6140	890110	S23.10	E015.25					
179-076	51792-08270	L890122/	HDDT	8888*	4312	890126	S23.11	E015.30					
179-076	51840-08263	L890305/	HDDT	8888*	1020	890315	S23.13	E015.30					
179-076	51856-08260	L890327/	HDDT	8888*	8080	890331	S23.12	E015.34					
179-076	51872-08261	[illegible]	HDDT	8888*	3020	890415	S23.13	E015.25					
179-076	51888-08255	L890430/	HDDT	8888*	0010	890502	S23.14	E015.26					
179-076	51904-08253	L890518/	HDDT	8888*	8000	890518	S23.14	E015.28					
179-076	[illegible]	L890527/	HDDT	8888*	4010	890603	S23.14	E015.24					
179-076	51936-08245	L890611/	HDDT	8888*	1020	890619	S23.14	E015.28					
179-076	51952-08244	L890705/	HDDT	8888*	3010	890705	S23.15	E015.26					
179-076	51968-08242	L890716/	HDDT	8888*	4140	890721	S23.15	E015.27	2494	2153			H19 45 7
179-076	51984-08240	L890730/	HDDT	8888*	1000	890806	S23.15	E015.26					
179-076	52016-08232	[illegible]	HDDT	8888*	[illegible]	890907	S23.14	E015.27					

Appendix 3.2: WRS 179-076 from 18th October 1987 to 7th October 1989.

SATELLITE APPLICATIONS CENTRE (P.O.BOX 395), PRETORIA, 0001 REPUBLIC OF SOUTH AFRICA

LANDSAT 5(MSS) SCENES AVAILABLE FOR WRS: 179-077 WITH MAX. CLOUDCOVER OF 50% FOR THE TIME PERIOD 21-MAR-84 TO 12-DEC-89.

WRS PATH ROW	SCENE ID	SOURCE No.	SOURCE TYPE	BAND QUALITY 12345678	CLOUD COVER	DATE	CENTER LAT.	CENTER LONG.	PRODUCT TAPE No.	FILM No.	STD PRODUCTS 123456789	TAS PRODUCTS 123456789	TAS PROCESS
179-077	50064-07244	LB405037/2	HDDT	88888*	3660	840504	S24.58	E014.98					
179-077	50080-07251	LB405157/1	HDDT	88888*	1111	840520	S24.58	E014.02					
179-077	50096-07251	LB406047/1	HDDT	88888*	0000	840605	S24.58	E014.00					
179-077	50112-07255	LB406187/2	HDDT	88888*	0000	840621	S24.58	E014.09					
179-077	50128-07260	LB407087/1	HDDT	88888*	5038	840707	S24.55	E014.91					
179-077	50144-07263	LB40722/1	HDDT	88888*	0000	840723	S24.58	E014.96					
179-077	50176-07273	LB40821/2	HDDT	88888*	0000	840824	S24.58	E014.72					
179-077	50192-07277	LB40907/2	HDDT	88888*	2222	840909	S24.58	E014.75					
179-077	50208-07274	LB40923/2	HDDT	88888*	1332	840925	S24.58	E014.74					
179-077	50224-07277	LB41009/2	HDDT	88888*	3770	841011	S24.58	E014.65					
179-077	50240-07281	LB41025/1	HDDT	88888*	6201	841027	S24.58	E014.91					
179-077	50256-07272	LB41111/1	HDDT	88888*	4001	841112	S24.58	E014.97					
179-077	50272-07272	LB41127/1	HDDT	88888*	9999	841128	S24.58	E015.00					
179-077	50288-07273	LB41213/1	HDDT	88888*	5850	841214	S24.58	E014.98					
179-077	50304-07274	LB41227/2	HDDT	88888*	5881	841230	S24.58	E014.96					
179-077	50320-07275	LB50115/1	HDDT	88888*	7851	850115	S24.58	E014.95					
179-077	50336-07275	LB50126/1	HDDT	88888*	2138	850131	S24.58	E014.95					
179-077	50368-07275	LB50304/1	HDDT	88888*	0000	850304	S24.58	E014.95					
179-077	50384-07275	LB50311/2	HDDT	88888*	5004	850320	S24.58	E014.95					
179-077	50400-07275	LB50331/2	HDDT	88888*	2070	850405	S24.58	E014.96					
179-077	50416-07275	LB50420/1	HDDT	88888*	0000	850421	S24.56	E014.97					
179-077	50432-07274	LB50506/2	HDDT	88888*	1000	850507	S24.56	E014.[illegible]					
179-077	50448-07274	LB50521/2	HDDT	88888*	1000	850523	S24.56	E014.[illegible]					
179-077	50464-07274	LB50606/2	HDDT	88888*	0000	850608	S24.56	E014.[illegible]					
179-077	50480-07273	LB50621/2	HDDT	88888*	0000	850624	S24.[illegible]	E014.[illegible]					
179-077	50496-07272	LB50709/1	HDDT	[illegible]	7001	850710	S24.[illegible]	E014.[illegible]					
179-077	50512-07271	LB50722/2	HDDT	[illegible]	[illegible]	850726	S24.[illegible]	E014.[illegible]					
179-077	50528-07271	LB50811/1	HDDT	[illegible]	[illegible]	850811	S24.[illegible]	E014.[illegible]					
179-077	50544-07270	LB50825/2	HDDT	[illegible]	[illegible]	850827	S24.[illegible]	E014.[illegible]					
179-077	50560-07265	LB50908/2	HDDT	[illegible]	1110	850912	S24.[illegible]	E014.[illegible]					
179-077	50592-07263	LB51013/1	HDDT	88888*	0000	851014	S24.58	E014.[illegible]					
179-077	50608-07261	LB51027/2	HDDT	8888*	[illegible]	851030	S24.58	E014.91					
179-077	50688-07245	LB60118/2	HDDT	88888*	3473	860118	S24.59	E014.05					
179-077	50704-07241	LB60132/2	HDDT	88888*	5004	860203	S24.57	E014.95					
179-077	50816-07215	LB60526/1	HDDT	88888*	1050	860526	S24.58	E014.89					
179-077	50832-07212	LB60607/2	HDDT	88888*	0390	860611	S24.59	E014.09					
179-077	50848-07205	LB60621/2	HDDT	88888*	2476	860627	S24.59	E014.80					
179-077	50864-07202	LB60710/2	HDDT	88888*	9192	860713	S24.59	E014.91					
179-077	50880-07194	LB60727/1	HDDT	88888*	0000	860729	S24.59	E014.93					
179-077	50896-07191	LB60812/2	HDDT	88888*	3030	860814	S24.59	E014.95					
179-077	50912-07183	LB60828/1	HDDT	88888*	1010	860830	S24.59	E014.97					
179-077	50928-07180	LB60914/1	HDDT	88888*	0000	860915	S24.59	E014.97					
179-077	50976-07163	LB61102/1	HDDT	88888*	7004	861102	S24.59	E014.92					
179-077	51008-07160	LB61202/1	HDDT	88888*	7042	861204	S24.56	E014.85					
179-077	51040-07155	LB61225	HDDT	88888*	5062	870105	S24.56	E014.89					
179-077	51072-07150	LB70131	HDDT	88888*	0000	870206	S24.54	E014.94					
179-077	51104-07140	LB70310	HDDT	88888*	2000	870310	S24.55	E014.93					
179-077	51120-07144	LB70320/2	HDDT	88888*	6092	870326	S24.56	E014.90					
179-077	51136-07200	LB70409/2	HDDT	88888*	2636	870411	S24.56	E014.96					
179-077	51168-07211	LB70510/2	HDDT	88888*	2021	870513	S24.55	E014.80					
179-077	51184-07214	LB70523/2	HDDT	88888*	0000	870529	S24.54	E014.89					
179-077	51200-07220	LB70613/2	HDDT	88888*	2121	870614	S24.56	E014.98					
179-077	51216-07222	LB70625/2	HDDT	88888*	5040	870630	S24.55	E014.94					
179-077	51248-07231	LB70720/2	HDDT	88888*	0000	870801	S24.56	E014.95					

Appendix 3.3: WRS 179-077 from 4th May 1984 to 1st September 1987.

Appendix 3.4: WRS 179-077 from 17th September 1987 to 7th October 1989.

SATELLITE APPLICATIONS CENTRE ,P.O.BOX 395 , PRETORIA ,0001 REPUBLIC OF SOUTH AFRICA

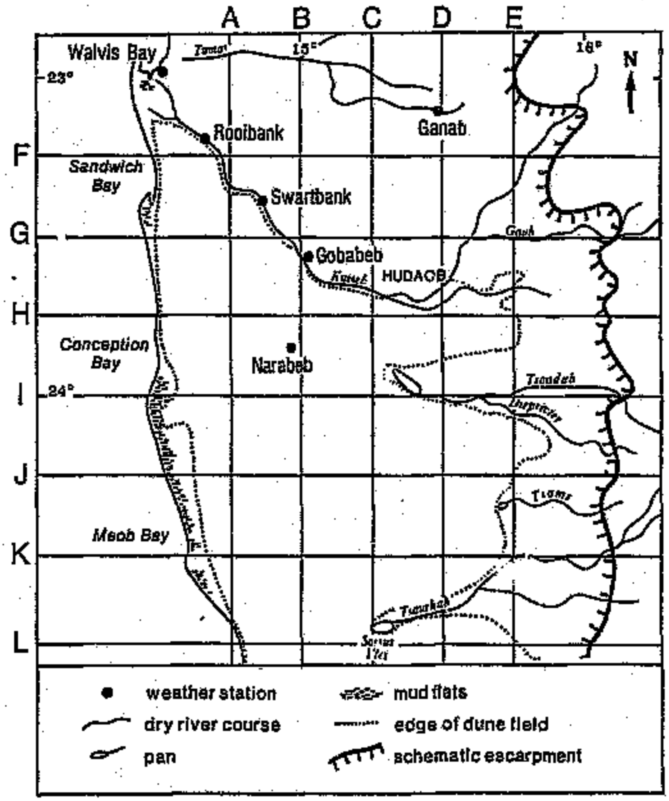
LANDSAT 5(MSS) SCENES AVAILABLE FOR WRS; 179-077 WITH MAX. CLOUDCOVER OF 50% FOR THE TIME PERIOD 24-MAR-84 TO 12-DEC-89.

WRS: TRK-FRM	SCENE ID	SOURCE No.	SOURCE TYPE	BAND QUALITY 12345678	CLOUD COVER	DATE	SCENE CENTER LAT.	LONG.	PRODUCT TAPE-No.	FILM No.	STD PRODUCTS 12345678PM	IAS PRODUCTS 12345678RM	IAS PROCESS
179-077	51264-07233	L8708137/	HDDT	8888*	0030	870817	S24.56	E014.87					
179-077	51296-07242	L8709187/	HDDT	8888*	2030	870918	S24.54	E014.96					
179-077	51312-07244	L8710047/	HDDT	8888*	8000	871004	S24.50	E014.94					
179-077	51328-07250	L8710157/	HDDT	8888*	6001	871020	S24.54	E014.96					
179-077	51344-07252	L8711057/	HDDT	8888*	3311	871105	S24.55	E014.96					
179-077	51376-07255	L8712077/	HDDT	8888*	4070	871207	S24.57	E014.96					
179-077	51392-07261	L8712237/	HDDT	8888*	0000	871223	S24.56	E014.97					
179-077	51408-07262	L8801087/	HDDT	8888*	5000	880108	S24.56	E014.96					
179-077	51424-07264	L8801247/	HDDT	8888*	1111	880124	S24.54	E014.95					
179-077	51472-07272	L8803127/	HDDT	8888*	2103	880312	S24.56	E014.94					
179-077	51520-07274	L8804297/	HDDT	8888*	0001	880429	S24.55	E014.95					
179-077	51536-07275	L8805157/	HDDT	8888*	3647	880515	S24.54	E014.93					
179-077	51568-07280	L8806167/	HDDT	8888*	0000	880616	S24.55	E014.91	2440	223		NIS	45 7
179-077	51600-07281	L8807187/	HDDT	8888*	2010	880718	S24.57	E014.90					
179-077	51616-07281	L8808037/	HDDT	8888*	5070	880803	S24.57	E014.91					
179-077	51680-07281	L8810067/	HDDT	8888*	6465	881006	S24.55	E014.90					
179-077	51696-07280	L8810227/	HDDT	8888*	1212	881022	S24.56	E014.90					
179-077	51744-07260	L8812097/	HDDT	8888*	4040	881209	S24.54	E014.93					
179-077	51760-07275	L8812257/	HDDT	8888*	0000	881225	S24.55	E014.93					
179-077	51776-07275	L8901107/	HDDT	8888*	1012	890110	S24.54	E014.91					
179-077	51792-07273	L8901267/	HDDT	8888*	4961	890126	S24.55	E014.95					
179-077	51840-07265	L8903157/	HDDT	8888*	3010	890315	S24.57	E014.96					
179-077	51856-07263	L8903317/	HDDT	8888*	0000	890331	S24.56	E015.00					
179-077	51872-07263	L8904167/	HDDT	8888*	5071	890416	S24.59	E014.91					
179-077	51888-07262	L8905027/	HDDT	8888*	3476	890502	S24.58	E014.91					
179-077	51904-07253	L8905187/	HDDT	8888*	0000	890518	S24.58	E014.93					
179-077	51920-07254	L8906037/	HDDT	8888*	1000	890603	S24.58	E014.90					
179-077	51936-07252	L8906197/	HDDT	8888*	3071	890619	S24.58	E014.93					
179-077	51952-07250	L8907057/	HDDT	8888*	0000	890705	S24.59	E014.92					
179-077	51968-07244	L8907217/	HDDT	8888*	0000	890721	S24.59	E014.92					
179-077	51984-07242	L8908067/	HDDT	8888*	0000	890806	S24.59	E014.92					
179-077	52016-07234	L8909077/	HDDT	8888*	0000	890907	S24.58	E014.92					

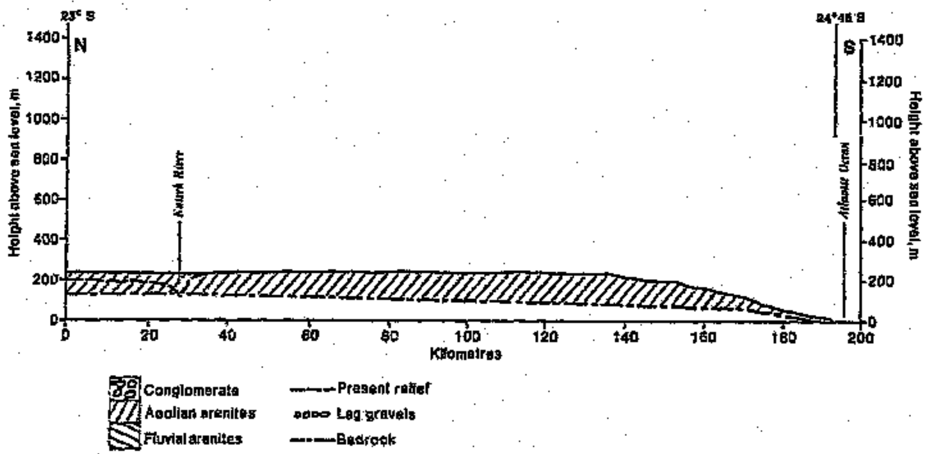
Appendix 4

Two Dimensional Sections of Sedimentation in the Central Namib

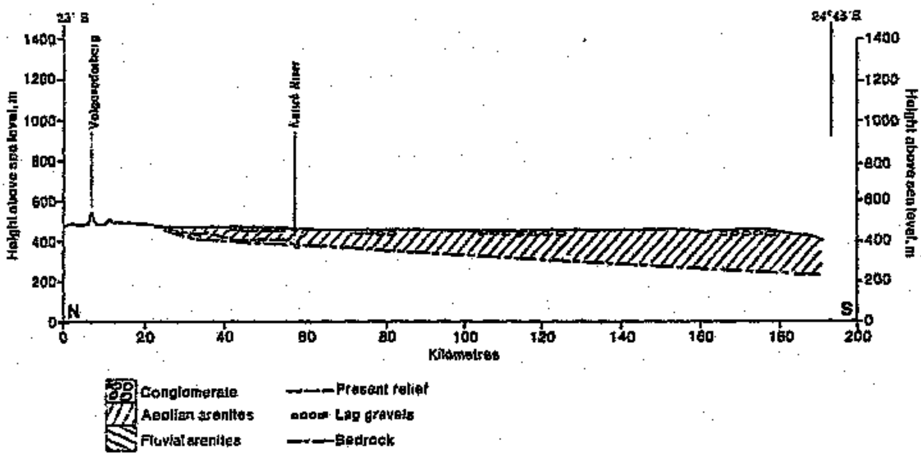
1. Base orientational map for cross sections.
2. Cross section A. 14°45' E.
3. Cross section B. 15° E.
4. Cross section C. 15°15' E.
5. Cross section D. 15°30' E.
6. Cross section E. 15°45' E.
7. Cross section F. 23°30' S.
8. Cross section G. 23°30' S.
9. Cross section H. 23°45' S.
10. Cross section I. 24° S.
11. Cross section J. 24°15' S.
12. Cross section K. 24°30' S.
13. Cross section L. 24°45' S.



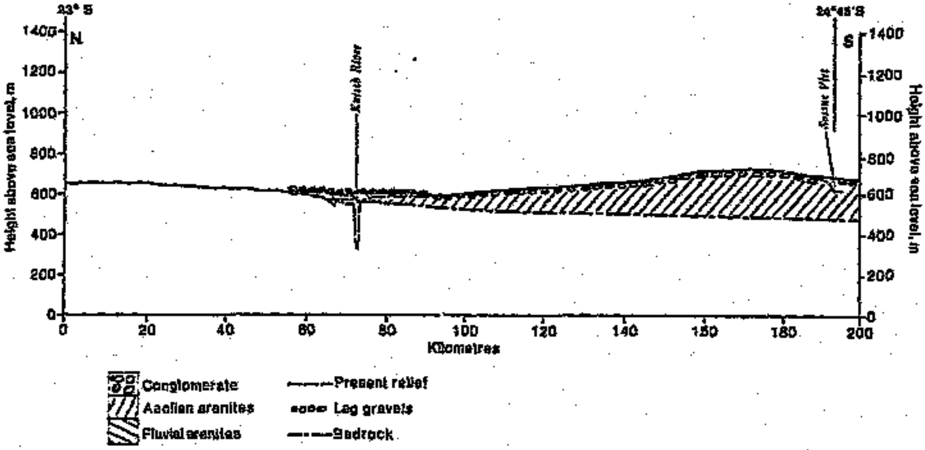
Appendix 4.1: Base orientational map for cross sections



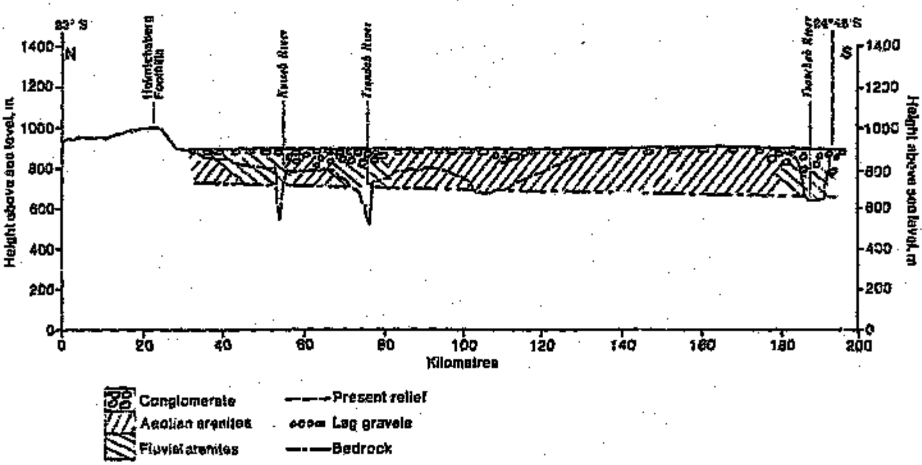
Appendix 4.2: Cross section A. 14°45' E.



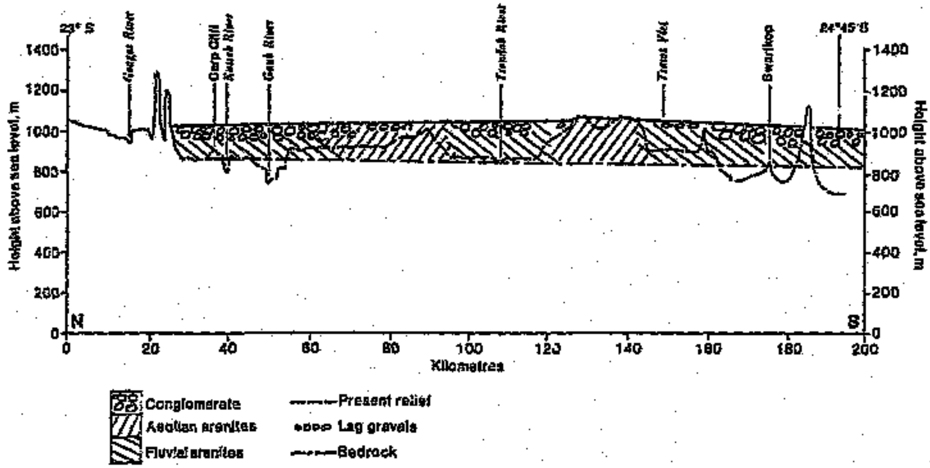
Appendix 4.3: Cross section B. 15° E.



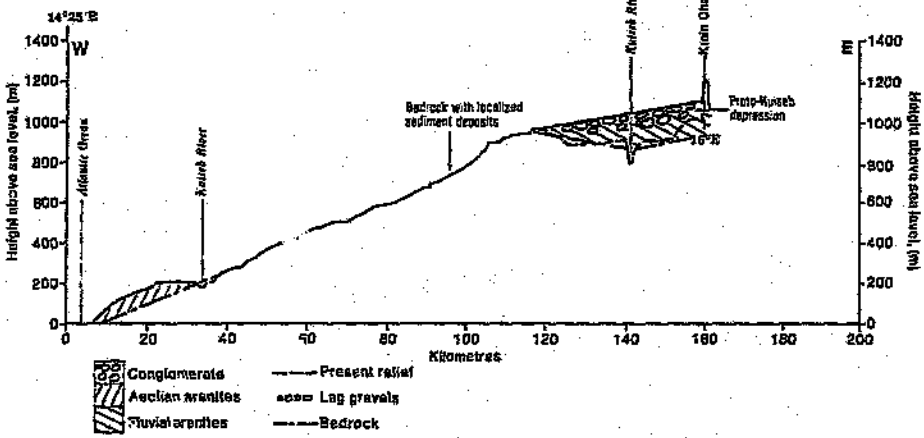
Appendix 4.4: Cross section C. 15°15' E.



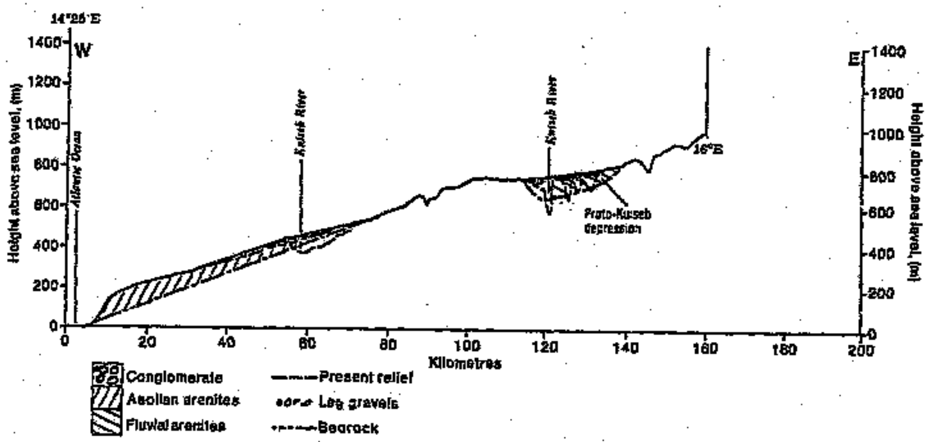
Appendix 4.5: Cross section D. 15°30' E.



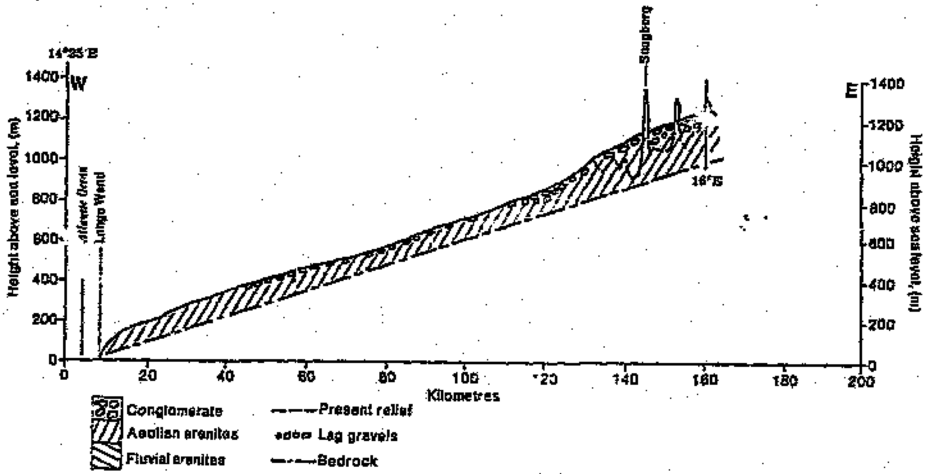
Appendix 4.6: Cross section E. 15°45′ E.



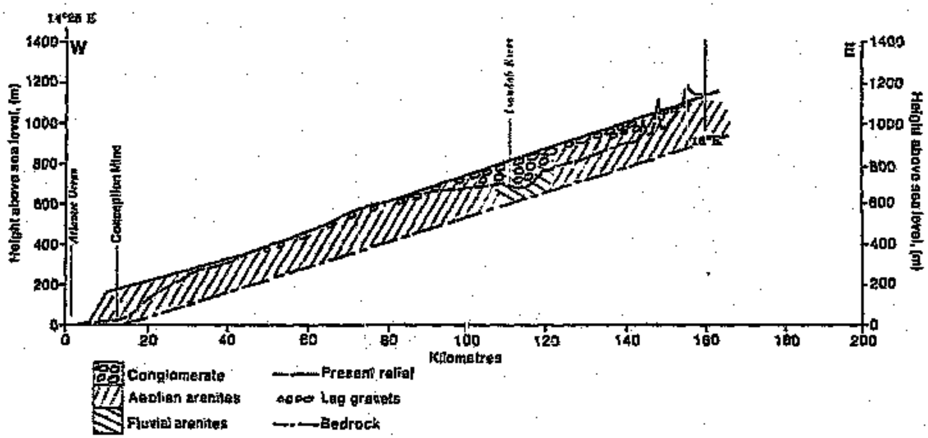
Appendix 4,7: Cross section F. 23°15' S.



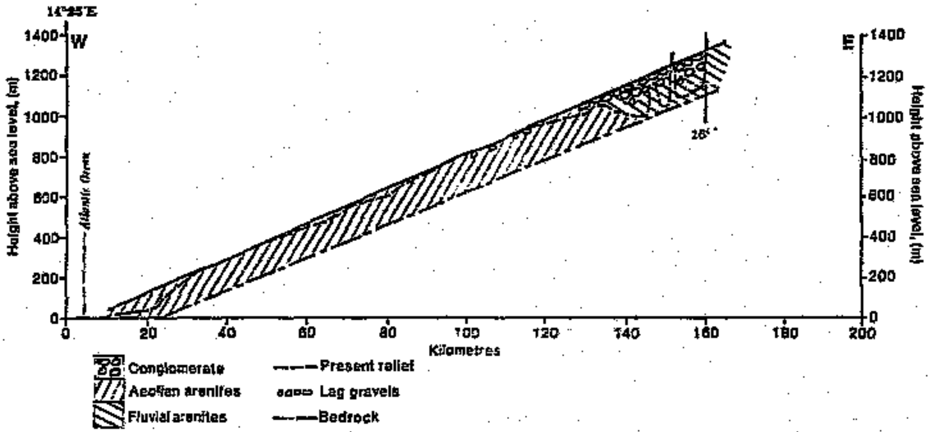
Appendix 4.8: Cross section G. 23°30' E.



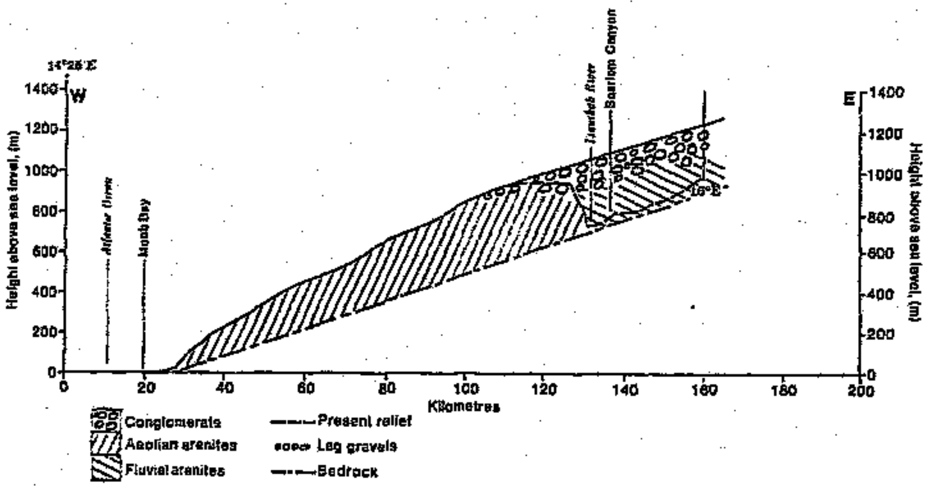
Appendix 4.9: Cross section H. 23°45' S.



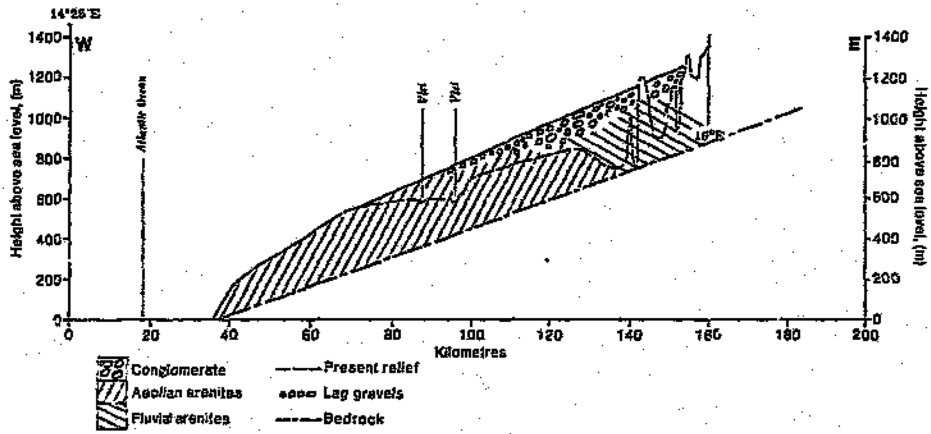
Appendix 4.10: Cross section I. 24° S.



Appendix 4.11: Cross section J. 24°15' S.



Appendix 4.12: Cross section K. 24°30' S.



Appendix 4.13: Cross section L. 24°45' S.