With many thanks, Smith

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Flash-flood sediments and ichnofacies of the Late Pleistocene Homeb Silts, Kuiseb River, Namibia

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ABSTRACT

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The Homeb Silt Formation consists of eroded remnants of fine-grained alluvium that were deposited within the Kuiseb River valley in southern Namibia during the Late Pleistocene. In Holocene times the river deeply incised its valley fill leaving steep walled "castles" of relict alluvium—the Homeb Silts. This study is based on the 25 m thick type exposure of Homeb Silts at Homeb and describes flash-flood sediments that were colonised by successive generations of opportunistic arthropods. The stacked flood units each comprise a massive tabular siltstone bed overlain by a narrower interval of rapidly alternating sandstone and siltstone with claystone veneers. These flood units are interpreted as having accumulated under semi-arid climatic conditions by episodic back-flooding of the Kuiseb River into embayments and tributary mouths.

Soon after deposition as the floodwaters subsided, the sediment was colonised by burrowing, sediment-ingesting organisms, mostly arthropods, that produced a *Taenidium* ichnofacies. After the floodwaters had drained, the exposed sediment was colonised by grasses and burrowed by terrestrial arthropods, probably ants and termites, resulting in an overprint of *Termitichnus* ichnofacies with associated pelletal chambers.

Thirteen "horizons" of rhizocretions and root tubules occur toward the top of the succession and indicate a gradual reduction in the frequency of flooding. These immature calcic palaeosols suggest that the climate in the Central Namib Desert 20,000 years ago was semi-arid, being wetter and more seasonal than the hyperarid conditions that prevail today.

Introduction

The Kuiseb River is one of the major ephemeral watercourses in Namibia that flows westward across the hyperarid Namib Desert towards the Atlantic Ocean (Fig. 1). During the Late Pleistocene the climate was less extreme than today and this is reflected in some relict alluvial terraces preserved in the rock-walled canyon of the Kuiseb valley. This report summarises a sedimentological and ichnological analysis of the ancient Kuiseb flood deposits with the aim of reconstructing the conditions which prevailed in the northern Namib some 20,000 years ago. The age of the Namib is controversial, but we support the viewpoint that aridity was established by end-Cretaceous to earliest Tertiary times, based on a detailed study of the post-Gondwana stratigraphic record fully discussed elsewhere (Ward et al., 1983; Ward, 1987; Ward and Corbett, 1990). This 60 Ma record has provided sufficient time for faunas to adapt to the arid environment. The modern Namib Desert is a relatively young Plio–Pleistocene phenomenon.

In its upper reaches, on the interior plateau of central Namibia, the Kuiseb River has eroded a shallow valley into Late Precambrian metasedi-

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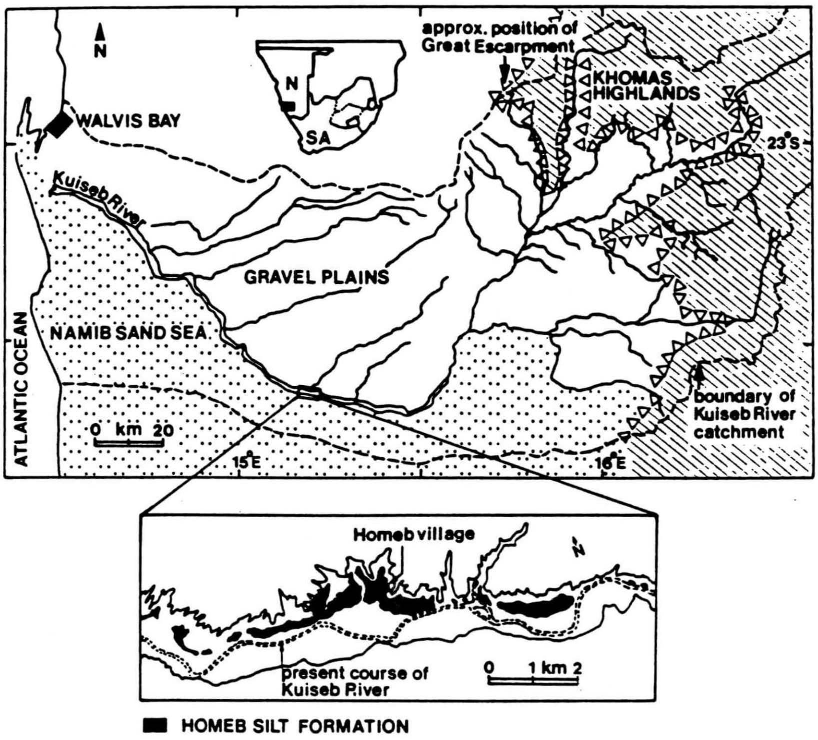

Fig. 1. Location of study area.

ments of the Damara Sequence. Eastward of the north–south trending escarpment that separates the highland plateau from the coastal plains, the river is deeply incised into bedrock forming a gorge 80 km long by 500 m wide and up to 200 m deep (Marker, 1977). Downstream of the "Kuiseb canyon" gorge, the valley widens and becomes progressively more indistinct until it merges with the coastal sabkhas in the vicinity of Walvis Bay.

Between the Escarpment and the coastal flats the Kuiseb valley is bounded on its southern side by the Namib Sand Sea and to the north by extensive gravel plains. Kuiseb floodwaters rarely penetrate the coastal dunes to reach the sea, thus

			LITHOSTRATIGRAPHIC UNITS	INTERPRETATION	
QUATERNARY	RECENT		Kuiseb River alluvium	Ephemeral, braided river, modern incised Kuiseb drainage system.	Namib Desert Phase
	PLEISTOCENE	Late	Sossus Sand Formation	Desert dunes and sand sheets of the main Namib Sand Sea.	
			Gobabeb Gravel Formation	Ephemeral, shallow braided river, resedimented gravels.	
			Khommabes Carbonate Member	Pans formed intermittently within Sossus Sand Formation.	
			Awa-gamteb muds	Early Kuiseb delta- coastal pans and dunes.	
			HOMEB SILT FORMATION	Fluvial flash-flood deposits of early Kuiseb River.	
		Middle	Hudoab Tufa Formation	CaCO precipitation at groundwater seeps.	
			Oswater Conglomerate Formation	Ephemeral braided river deposits of ancestral incised Kuiseb.	
		Early			
			▲▲▲▲▲▲▲▲▲▲▲▲▲▲▲▲▲	Epeirogenic uplift initiates incision of Kuiseb drainage net.	Pedogenic Phase
TERTIARY	NEOGENE	Pliocene	Kamberg Calcrete Formation		
		Miocene			

Fig. 2. Cenozoic stratigraphy of the Kuiseb canyon area from Ward (1987).

the Namib sands are able to migrate across the end-point "delta" to form a narrow dunefield on the north bank extending to Walvis Bay.

The Cenozoic deposits of the Kuiseb valley have been well documented by Ward (1987) and Ward and Corbett (1990) who recognise ten sedimentary units (Fig. 2) that accumulated as a result of 5 major tectono-climatic events which have affected the Namib region since the break-up of Gondwana during the Cretaceous. These are: (1) post-Gondwana erosion phase—Late Cretaceous; (2) proto-Namib desert phase—Palaeogene; (3) Karpfenkliff fluvial phase—Miocene; (4) pedogenic phase—end Miocene; (5) Namib Desert phase—Pliocene.

The Homeb Silt Formation consists of eroded remnants of fine-grained alluvium deposited within the Kuiseb valley some 20,000 years ago (Ward, 1987) during the last aggradational stage of the Namib Desert phase (Fig. 2). They are preserved mainly in the Kuiseb canyon section as isolated "castle-shaped" outcrops hanging from the rock walls of tributary valleys that enter from the northern gravel plains. The maximum thickness recorded in any single exposure is about 25 m, although the most elevated strata are some 45 m above the present Kuiseb River bed. Elevations of the basal exposures of Homeb sediments, which lie unconformably on the Damaran schists, range from 1 to 30 m above the river bed.

Previous workers have recognised sedimentary sequences within the flat-lying Homeb Silts that are characteristic of ponded overbank ("vlei") deposits and have offered several explanations as to their mode of origin: (1) sediments deposited behind a dune dam(s) (Goudie, 1972: Scholz, 1972; Rust and Weinke, 1974, 1980); (2) river end-point accumulations (Marker and Muller, 1978; Vogel, 1982); (3) flood deposits of an aggrading river (Ollier, 1977).

Marker and Muller (1978) propose that aridification of the Kuiseb catchment allowed a sand dune-barrier to form in the delta section with subsequent ponding of seasonal floodwaters in the middle canyon resulting in accumulation of the Homeb fines. This scenario is similar to the series of dune-dam deposits envisioned by Rust and Weinke (1980) as the end-point migrated upstream (Seely and Sandelowsky, 1974). Tsondab Vlei and Sossus Vlei are modern analogues of this type of dune-dam deposit, albeit in a less laterally restricted environment. The two vleis are

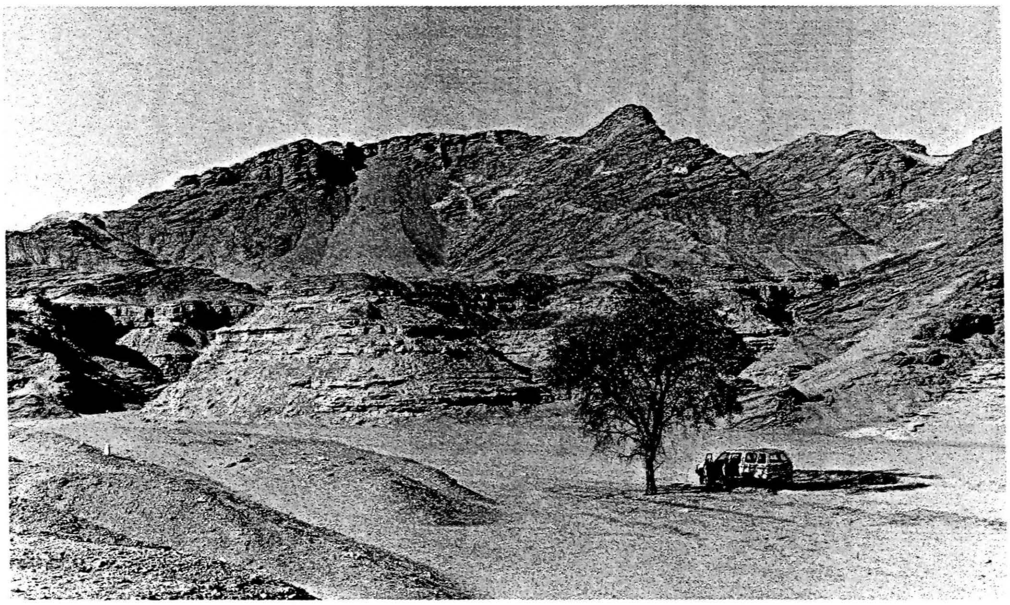

Fig. 3. View of study section at Homeb showing a recent terrace in the foreground, the type exposure of the Homeb Silt Formation in the centre and outcrops of Middle Proterozoic Damara Schist forming the canyon walls in the background.

the end-points of the Tsondab and Sossus rivers, which never reach the Atlantic, but now form ephemeral playa-like deposits in the middle of the Namib sand sea. Ollier (1977) and Ward (1987) depart from this general model in proposing a purely fluvial model whereby the silts were deposited during flash-flood events by rapid sedimentation from eddying currents as the floodwaters inundated the side valleys of the Kuiseb canyon.

This study concentrates on the type locality of the Homeb Silt Formation near the small Topnaar settlement of Homeb situated within the middle canyon section of the Kuiseb River (Fig. 3). Previous sedimentological studies on these sediments have been mainly descriptive and aimed at defining their stratigraphic context. Our objective is to refine the palaeoenvironmental interpretation with detailed observation and analysis of sedimentation and subsequent biological

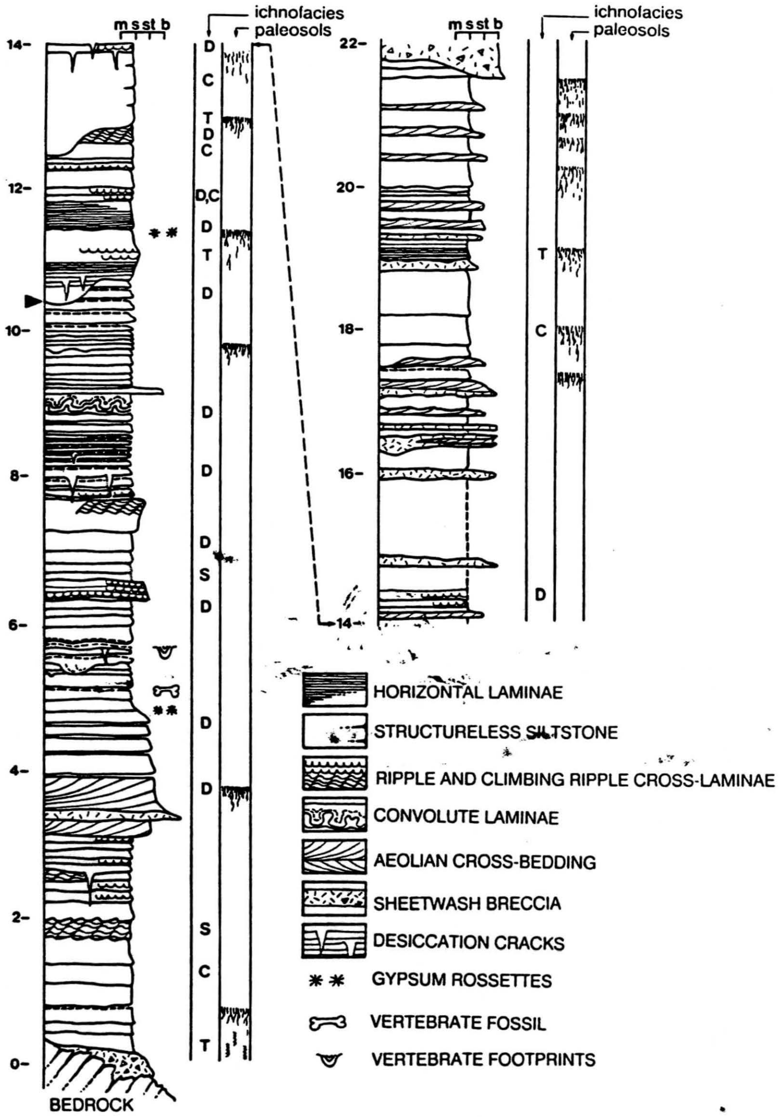

Fig. 4. Columnar log of the Homeb Silt Formation at the type section showing sedimentary structures, paleosols and ichnofacies. The major erosion surface arrowed at 10.5 m is possibly a regional disconformity; *m* = mudstone, *s* = siltstone, *st* = fine-grained sandstone, *b* = pebble breccia. Scale in metres.

colonisation of the Homeb Silts. This is achieved through detailed logging of 2-dimensional panel sections with emphasis on the sedimentary fabrics and cross-cutting relationships of the numerous trace fossils.

Lithology and sedimentary structures

The Homeb succession mainly consists of semi-consolidated, micaceous, light yellowish-brown (2.5Y 6/4) to light olive-grey (5Y 6/2) muddy siltstone with minor but persistent light grey (2.5Y 7/0) claystone veneers. Rare intercalations of reddish-brown (2.5YR 4/4) aeolian sandstone and locally derived sheetwash breccias occur in the type section especially towards the top of the succession (Fig. 4, 16–22 m). Very thin (5 mm) sheets of indurated ferricrete coincide with the top surface of some of the muddy siltstone beds. Every bed is bioturbated to some degree ranging from sparse burrows to a fully reworked ichnofabric. The various trace fossils and their ichnofacies are described later in this report.

The outcrop pattern is characterised by "thinning-upward" sequences comprising prominent tabular beds of apparently structureless muddy siltstone between 0.1 m and 2.0 m thick, overlain by up to 1.0 m thick intervals of rapidly alternating (0.1–0.25 m) wavy beds of biotite-rich sandy siltstone, fine-grained sandstone and claystone veneers. Basal contacts of the massive muddy siltstone beds are commonly uneven with wide, channel-like scours that have eroded up to 0.5 m into the underlying rapidly alternating unit (Fig. 5). No gravels are associated with the scours in the study section but they have been observed in nearby exposures (Ward, 1987). The vertical succession of Homeb sediments exposed at the type locality consists of at least 13 erosively based sequences, each between 0.3 and 2.5 m thick (Fig. 4). One of the basal scour surfaces (10.6 m above bedrock at the type locality, see Fig. 4) can be traced throughout all the outcrops in the Homeb area and is possibly of regional significance. The succession above the disconformity contains thicker muddy siltstone beds, fewer alternating beds and more bedrock breccias than lower down. The breccias in these upper strata commonly grade upward into reddish-brown, aeolian cross-bedded sandstone.

Closer examination of wind-etched faces along a cliff section (Fig. 6) shows the "structureless" beds of muddy siltstone to be mainly horizontally laminated at the base, passing upward through ripple and climbing ripple cross-laminae into a gradationally based, sharp-topped mudstone veneer that commonly displays polygonal desiccation cracks (Fig. 8). The overlying silty sandstone alternations are commonly ripple-drift cross-laminated with angles of climb between 25 and 35 degrees (Fig. 7). Rarely lenses of millimetre-sized faecal pellets are preserved in the ripple troughs. Bedding planes throughout this unit are characteristically undulatory and penetrated by numerous vertical burrows. The claystone veneers commonly preserve the ripple topography onto which they were deposited. In the detailed panel sections the veneers tend to occur in closely spaced bundles.

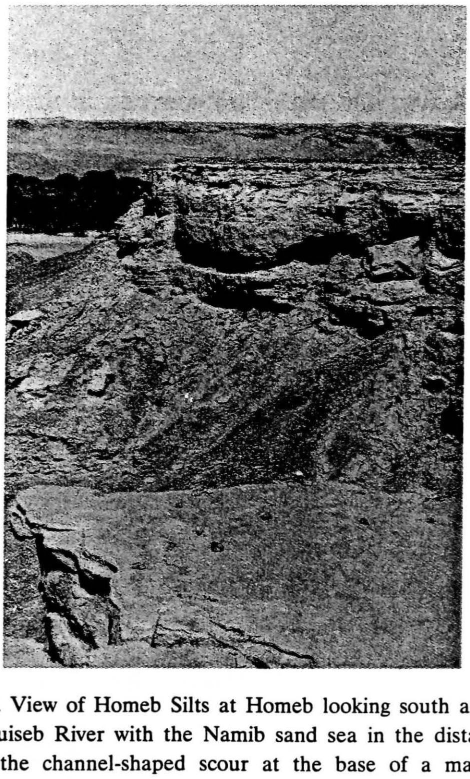

Fig. 5. View of Homeb Silts at Homeb looking south across the Kuiseb River with the Namib sand sea in the distance. Note the channel-shaped scour at the base of a massive siltstone in the middle distance and its mudcracked upper surface in the foreground.

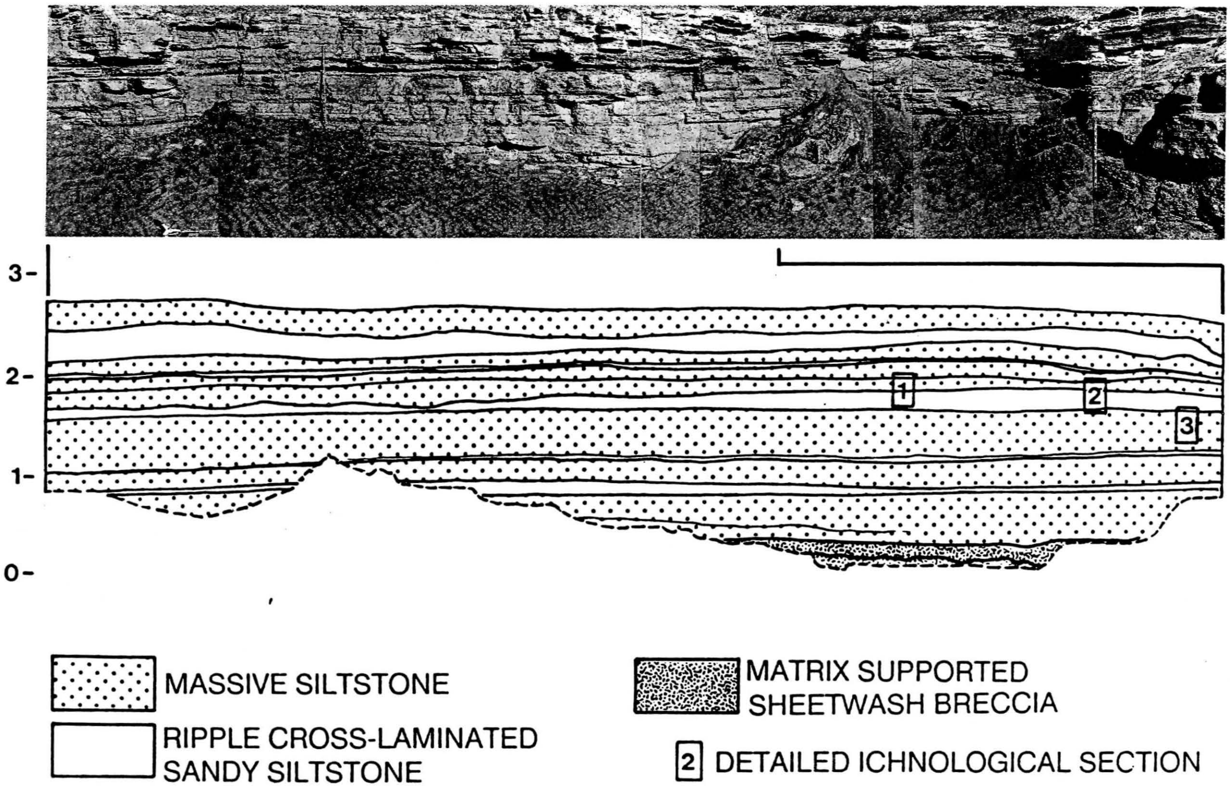

Fig. 6. Macrostratigraphic panel section showing lithofacies and bedding along a cliff exposure of the Homeb Silt Formation at the type locality.

Desiccation cracks are common in the upper, sandier portion of the depositional sequences where they have been the focus of intense bioturbation and calcification. Many are filled with an open network of calcareous laminae and some have been scoured and partially plugged with muddy silt during subsequent floods. More rarely, raindrop impressions attest to the subaerial exposure of the silts.

Thin beds of reddish-brown, micaceous, fine-

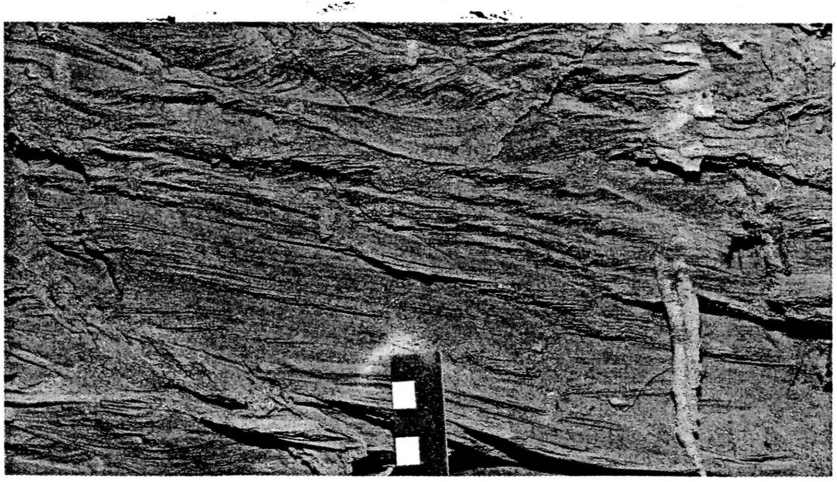

Fig. 7. Climbing ripple cross-lamination in silty sandstone of the Homeb Silt Formation. Two vertical backfilled burrows (*Skolithos*) have been exhumed by wind-etching. Scale in cm.

grained sandstone occur sporadically throughout the succession, but are more common in the uppermost 4 m where they are gradationally interbedded with sheetwash breccias. They are distinctively cross-bedded with high angle (35 degree) dune foresets, the topsets of which are invariably eroded by fluvial action. These are interpreted as the remnants of barchanoid dunes that migrated across the floodplain between flood events.

No penecontemporaneous deformation features were observed at the type locality although flame structures have been recorded in other Homeb outcrops (Marker and Muller, 1978; Ward, 1987). Isolated dish-like structures that occur in some of the alternating sand/silt units are similar to load-casts (Fig. 9) but are interpreted as hoofprints (Allen, 1989; Loope, 1986) of medium-sized bovids. A clearly defined trackway of 25 circular hoofprints exposed on a nearby siltstone surface supports this interpretation.

The preferential calcification of porosity interfaces such as roots, mudcracks and backfilled burrows provides evidence of early pedo-diagenetic modification of the alluvium. Roots are preserved as root moulds, root tubules, rootcasts and rhizocretions (Fig. 10; Klappa, 1980), and having properly distinguished them from similar looking burrow systems, it is apparent that they are not nearly as abundant as previously logged (Marker and Muller, 1978). A few discontinuity surfaces within the muddy siltstones are indurated with dark brown ferricrete and have the appearance of diastems or hiatus surfaces. The 22 m section at Homeb contains 13 superimposed "horizons" of rhizocretions and root tubules (Klappa, 1980; Fig. 10), most of which occur in the upper 6 m of the succession. These too represent depositional hiatuses during which sedimentation rates were negligible, slower than the rates of pedogenesis. Estimates of the duration of these

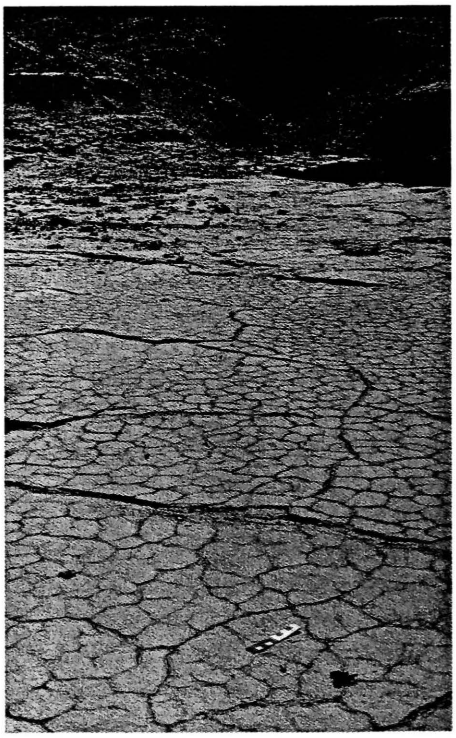

Fig. 8. Two generations of mudcracks on top of the thick massive siltstone unit in Fig. 5. Scale is 10 cm long.

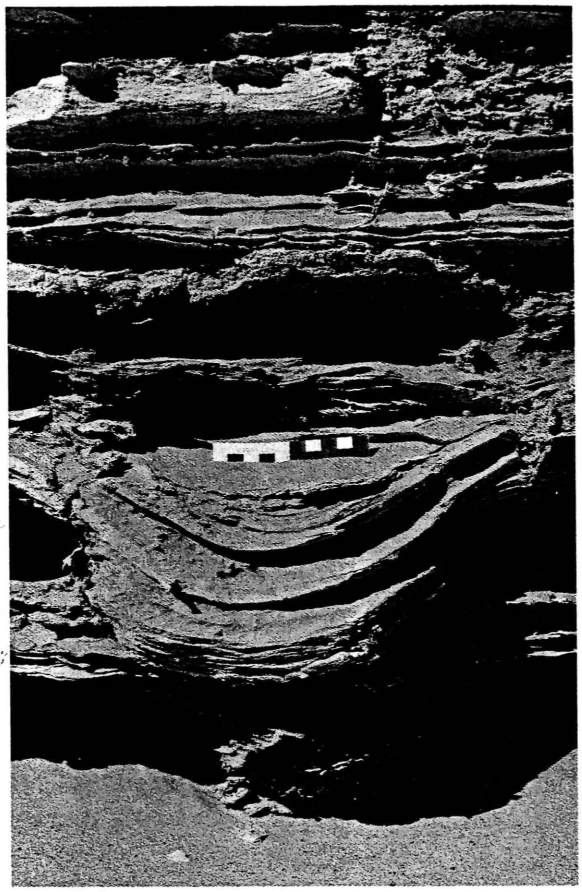

Fig. 9. A distinctive U-shaped deformation structure in a cliff exposure of Homeb Silt strata at Homeb which is interpreted as a hoofprint of a gemsbok-sized animal. Scale in cm.

periods of negligible sediment accumulation are difficult to make because rates of pedogenesis were determined by several extrinsic factors including climate and base-level movements which are as yet undetermined. Nevertheless, the horizons of calcareous rhizocretions (Klappa, 1980) do indicate that parts of the Kuiseb floodplains were colonised by fibrous rooted grasses which suggest periods of non-deposition lasting at least 2–10 years. The increase in number of palaeosols towards the top of the succession suggests a gradual decrease in frequency of flooding, which is perhaps due to increased aridification of the Kuiseb catchment.

Comparison of the Homeb rooted horizons with calcic soils developed on modern semi-arid floodplains (Butler, 1958; Sehgal and Stoops, 1972) and Pliocene to recent calcretes (Watts, 1977; Netterberg, 1980; Semeniuk and Searle, 1985) indicates that the Homeb climate was warm to hot (mean annual temperatures of 16–20°C) with a seasonal rainfall of around 500 mm/y. Under such conditions the Homeb floodplains were essentially dry with capillary-rise dominant over leaching. This would have promoted the early calcification of roots, desiccation cracks and organically lined burrows in the incipient Bca horizon some 10–50 cm below surface.

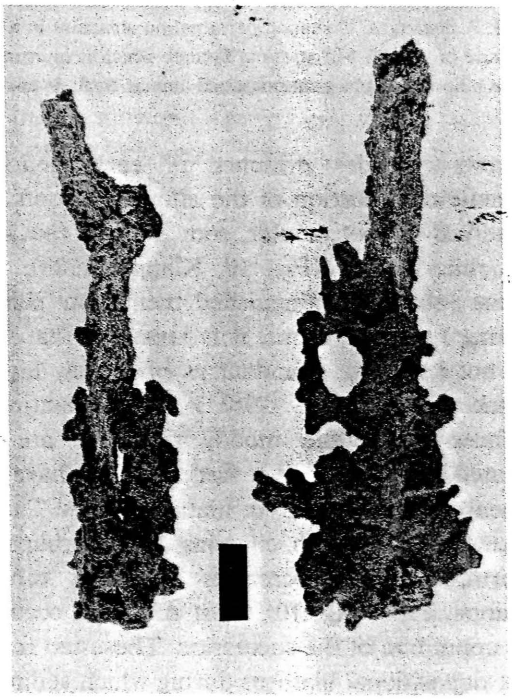

Fig. 10. Carbonate encrusted rhizocretions from the Homeb Silt Formation. Scale in cm.

Fig. 11. Gypsum rosettes from the type exposure of the Homeb Silt Formation (see Fig. 4) showing holes (arrowed) made by the *Skolithos* trace maker. Scale in cm.

Gypsum "rosettes" that are firmly embedded in the muddy siltstone facies were logged at several horizons throughout the succession. They occur in two distinct crystal aggregates: compact spherical rosettes and flattened lenticular twins (Cody and Cody, 1988; Cody, 1991; Fig. 11). Some of the flattened rosettes have been penetrated by meniscate burrows to leave circular holes in the gypsum blades. In places where the Homeb alluvium is deeply weathered and the resulting regolith has been able to accumulate, the surface may be covered in clusters of miniature (5–10 mm) "desert rose"-type gypsum aggregates which are obviously recent and still being formed. These are distinctly different in crystal habit, size and mineralogy from the relict forms. The precipitation of penecontemporaneous gypsum in the Homeb alluvium indicates that these parts of the floodplain were subjected to playa-like evaporative conditions.

Body fossils are very scarce in the Homeb, a few small gastropods (Marker and Muller, 1978) from both aquatic (*Bulinus tropicus* and *Biomphaleria pfeifferi*) and terrestrial (*Xerocerastus* sp., *Sculptaria sculptuici*) habitats have been found as well as a single small rodent skeleton (*Paratymus* sp., Ward, 1987). During the course of this study some fragments of mineralised ostrich shell and the articulated limb bones of a gemsbok (*Oryx gazella*; G. Avery, pers. commun.) were found on the surface of the Homeb Silts in the type locality. The bone is undoubtedly old and calcified and was at some time embedded in the Homeb sediments, but it cannot be unequivocally linked to the time of Homeb deposition.

The geomorphic setting and sedimentary structures of the Homeb Silt Formation are similar to the remnant flood deposits preserved in "embayments" of the Colorado River (McKee, 1938). The Homeb strata closely resemble "slack-water" deposits of the Pecos River, western Texas, described by Patton et al. (1979), and the side channel deposits of the massive Pleistocene floods that resulted from the draining of the ice-dammed Lake Missoula in eastern Washington (Baker, 1973). These workers noted that, despite their popular name the bulk of the sedimentation in these embayments is essentially episodic and very rapid, resulting from a periodic influx of sediment-laden floodwaters. True "slack-water" deposits comprising organic-rich laminated clays are, in reality, a very minor component of the sedimentary pile in these embayments.

Despite the overall fine-grained texture of the Homeb sediments, there is an abundance of upper flow-regime plane beds and ripple-drift cross-lamination structures indicating rapid deposition from shallow fast-flowing, sediment-laden unidirectional flows that are typical of flash-flood fluvial systems (McKee et al., 1967; Frostick and Reid, 1977). Interestingly, the palaeo-flow direction throughout the measured section is to the north, up the tributary valley. This is perpendicular to, and away from the present Kuiseb River. Thus it is apparent that the Homeb Silt Formation was deposited in the tributary valleys by floodwaters of the Kuiseb River rather than the tributary itself, and that these floods were frequent enough to not allow enough time for pedogenic modification of the surficial alluvium.

Trace fossils

Introduction

Trace fossils are common throughout the Homeb succession although generally not in abundances that completely destroy the original sedimentary fabric. Using the six ichnofabric indices established by Droser and Bottjer (1986, 1989) the Homeb sediments have indices of 3 or 4. Invertebrate burrow casts are commonly exposed in full relief, revealing intricate details of their external and internal morphology and their cross-cutting relationships. The initial impression is that vertical burrows dominate the ichnofauna, but closer inspection shows that inclined and horizontal burrows are equally abundant. Fallen blocks which expose bedding surfaces to wind-etching erosion are covered with exquisitely preserved trace fossils. Bedding surfaces show numerous small oval or rounded depressions, and small hemispherical pustules of similar dimensions (about 5 mm in diameter) caused by vertical burrows that intersect the bedding plane. There are also trails and trackways between burrows which are reminiscent of arthropod trails in shallow marine deposits.

Most of the invertebrate burrows in the Homeb succession are without well-defined walls, and have been actively filled or "stuffed" with a mixture of sand and pelletal silt that weathers into conspicuous meniscus-shaped laminae. Two types of meniscate burrow-fill and two types of non-meniscate burrow-fill are recognised in the type section along with two types of palaeo- termitaria, various faecal pellet chambers, root traces and an arthropod track. These are described below and their associations and cross-cutting relationships discussed in terms of ichnofacies tiering (Bromley, 1990).

Nomenclature problem

Before describing the ichnofauna it is necessary to discuss current thinking about trace fossil nomenclature. According to Seilacher's pioneering classification (1967), these Namibian trace fossils belong to the continental *Scoyenia* ichnofacies, but the trace fossil *Scoyenia* is poorly known and rarely encountered. Seilacher's classification scheme is based on the primary assumption that trace fossil distribution is controlled by bathymetry. Recent workers have emphasised that this is fortuitous, as the other controlling factors which affect animal distribution (light penetration, food supply, oxygen content etc.) are also ultimately influenced by water depth (Ekdale, 1988; Byers, 1982). Seilacher's scheme also uses salinity as a factor in ichnofaunal nomenclature, and it has been implicitly assumed that each marine ichnofauna has a terrestrial equivalent. Thus the ichnogenus *Scolicia* was regarded as marine, and similar traces in the non-marine environment therefore required a different name.

A recent seminal paper by Bromley and Asgaard (1991) resolves the dilemma. These authors suggest that it is more sensible to ignore salinity constraints and bathymetry (Ekdale, 1988) and consider ichnofacies as either comparable to pure sedimentary facies, or as representative of the substrate consistency. By removing salinity constraints and recognising that similar trace fossil structures may occur in both non-marine and marine settings, the problematical *Scoyenia* ichnofacies may be abandoned. According to the Bromley and Asgaard classification outlined in Fig. 12 the Namibian trace fossils discussed in this paper are best described as belonging to their newly defined Arenicolites ichnofacies. Even though the Homeb Silts contain abundant *Skolithos* burrows, they are not assigned to the *Skolithos* ichnofacies because the latter is characteristic of high-energy environments with repeated episodes of erosion whereas the Homeb deposits were rapidly deposited in an otherwise low-energy environment then and rapidly colonised by sub-aqueous opportunistic organisms. The pioneer community was subsequently overwhelmed by hostile environmental changes during emergence and sub-aerial desiccation and in this case the sub-aqueous traces were reworked by terrestrial organisms.

ICHNOFACIES

GROUP 1
CONTROLLED BY SEDIMENTARY FACIES
AND ENERGY LEVELS

Skolithos: High
Cruziana: Intermittent high
Zoophycos: Low
Nereites: Very low
Psilonichnus: Supratidal high

GROUP 2
CONTROLLED BY RESISTANCE
OF SUBSTRATE

Trypanites: Hard
Glossofungites: Firm
Teredolites: Wood

Plus:
Arenicolites Ichnofacies
Short term opportunistic occurrences
in incongruous settings

Fig. 12. Bromley and Asgaard's grouping of ichnofacies as responses to substrate consistency and energy levels in different sedimentary facies. Note that the ichnogenus name used to define the ichnofacies is not italicised.

It is notable that since the "terrestrial" *Scoyenia* ichnofacies was established (Seilacher, 1967), it has been problematic. Seilacher (1978) and Frey et al. (1984) concluded that this was a low-diversity assemblage with few unique trace fossils, being very similar to marine assemblages. Bromley and Asgaard's (1991) suggestion is that if the salinity factor is ignored, the *Scoyenia* ichnofacies may be relegated to an historic footnote. Other trace fossil experts will doubtless disagree with this viewpoint, preferring to retain the older concepts and terminology. A similar nomenclatural problem has been addressed before, in Triassic deposits of East Greenland, from which Bromley and Asgaard (1979) described trace fossils which the "traditionalists" would have termed *Isopodichnus*, and the "pragmatists" would have discussed as ichnospecies of *Cruziana* and *Rusophycus*.

The pragmatic approach is becoming more acceptable and "salinity breaking ichnogenera" described by Ekdale et al. (1984, *Steinichnus* became *Spongeliomorpha*), Merrill (1984, non-marine *Ophiomorpha*), Bromley and Asgaard (1979) and Bromley (1990, *Isopodichnus* becomes *Rusophycus* or *Cruziana*) have entered the literature just as "ichnofacies breaking forms" were previously noted (Osgood, 1970; Turner et al., 1981; Mason et al., 1983). It is easier to apply the pragmatic nomenclatural philosophy, and because it strengthens the application of the ichofacies concept, it is adopted in this paper.

The nomenclature of these trace fossils is problematic until it is realised that the names are merely convenient labels, and that in such an environment the dominant organisms would have been re-selected opportunists (Bromley, 1990), capable of rapidly exploiting a new food source. In this case it is most likely that they were sediment ingesters, gleaning their nutrition from comminuted organic matter in freshly deposited sediment. The primary colonisers would then have become targets of other organisms, as prey, or as providers of a food source for coprophagic feeders. Micro-organisms would have presumably been present as a crucial part of the food web and may have used the faecal matter as a nutritious substrate.

In the past 10 years a number of important revisions of trace fossil systematics has been published, and they have served to clarify much of the confusing nomenclature which formerly burdened the subject. An ichnofauna from an environmental setting similar to the Namibian examples has been described by Ekdale and Picard (1985) from a Jurassic aeolianite (the Entrada Sandstone) in east-central Utah. They described a trace fossil *Entradichnus* which is now regarded as a junior synonym of *Taenidium* (D'Alessandro and Bromley, 1987). They also ascribed small vertical tubes to a new ichnogenus *Pustulichnus*, which they claimed was related to the activities of the *Entradichnus*-producing organism, or to the work of sand wasps. In the same paper, *Digitichnus* is described as an unlined, unbranched, vertical trace fossil with a planar laminated internal fill. Following the pragmatist school of ichnological thinking, *Digitichnus* is best considered as a junior synonym of *Skolithos*. We also consider it likely that these structureless *Skolithos* (equivalent to Ekdale and Picard's *Digitichnus)* are variants of the meniscate *Taenidium*, and that the two are intimately related, to the extent that they were made by the same or similar organisms. Ekdale and Picard (1985) drew similar conclusions from their material.

The large number of trace fossils in the Namibian outcrops clearly demonstrate that preservation is an important factor that influences identification. Lined burrows which are apparently internally structureless (*Palaeophycus*) can, in the same specimen, show internal meniscae (*Taenidium*) or other internal textures (*Planolites*), depending on the degree of sand blasting caused by the wind. Originally we used the name *Digitichnus* as a general field identification, but we now believe that these vertical traces ought to be named after the commoner ichnogenus *Skolithos*.

Description of trace fossils

Nine ichnofaunal elements in the Homeb Silt beds are described below. The dominant ichnofossils are *Skolithos* and *Taenidium*.

1. Ichnogenus Skolithos

The *Skolithos* burrows vary in diameter (average 5–8 mm), and although most are oriented perpendicular to bedding, some are inclined and become nearly parallel. Following ichnological convention, these are better named *Planolites* or *Palaeophycus*, depending on the type of burrow fill. As would be expected from an active organism, there is considerable variation in size and infill. In most examples the burrows are filled with the same fine-grained sediment in which they are constructed. The fill commonly displays a concentric orientation of the platy mica crystals with their long axes parallel to the burrow wall. In tangential sections the micaceous layers appear as meniscae. Few burrows have a distinct wall, and the *Skolithos* burrows rarely cross each other, although occasional bridging structures between burrows were observed. Many of the burrows contain small millimetre-sized cemented silt pellets, which are likely to have been generated by the animal which made the burrows.

1.1 *Skolithos linearis*. Vertical cylindrical burrows about 5 mm in diameter which occur individually in horizontally laminated muddy siltstone and terminate on a single mud-draped discontinuity surface. The burrow length varies according to thickness of the bed, but in a 400 mm bed they are of the order of 150 mm long. These burrows are filled with homogeneous fine silt, and the fill

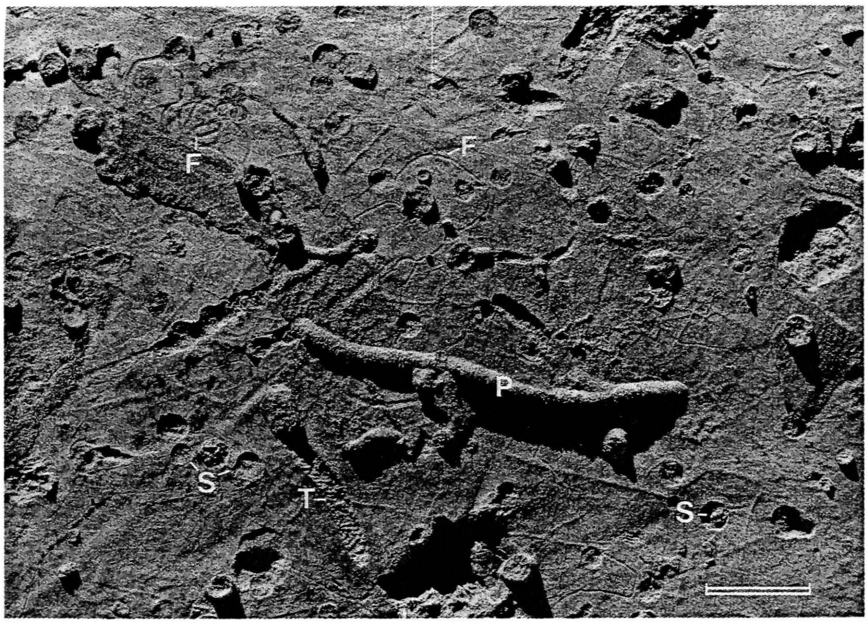

Fig. 13. Mudstone veneered siltstone surface displaying a variety of trace fossils of the Arenicolites ichnofacies. *P* = *Planolites*, *S* = *Skolithos*, *T* = *Taenidium*, *F* = Fodinichnia indet. Scale bar is 2 cm.

is non-meniscate. Some of them appear to expand upwards into a funnel shape and thus may be named *Monocraterion*. These *Skolithos* burrows are often cross-cut by rootlets and they penetrate the pellet-filled chambers. They are interpreted as vertical dwelling burrows formed when there was standing water above the sediment. Even though no U-shaped burrows were observed, these are assigned to the Arenicolites ichnofacies.

2. Ichnogenus Planolites (Fig. 13)

Horizontal burrows with a different coloured fill, displaying no wall or burrow lining, are here described as *Planolites*. They are locally abundant, but are best seen on fallen blocks where the bedding planes have been gently sand-blasted by the wind. Fresh surfaces contain many ichnofossils, but they are difficult to see until the wind has done its work. The burrows are slightly elliptical in cross-section, averaging 6 mm in diameter and may be up to 270 mm long. The burrow fill is not meniscate. Smaller (2 mm) burrows with curvilinear C- or ?-shapes occur associated with these *Planolites*. The *Planolites* burrows tend to both overlie and cross-cut each other. They are also found with horizontal pellet-filled burrows, but we believe that these are related to *Taenidium*, and may be a variant of the ichnospecies *Taenidium satanassi* described by D'Alessandro and Bromley (1987).

3. Ichnogenus Taenidium (Figs. 14, 18, 19)

Taenidium is an unlined burrow with no visible burrow wall. They may be horizontal, vertical, inclined, or curvilinear. The burrows are back-

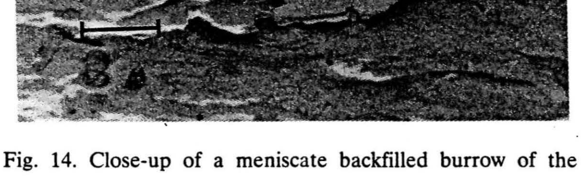

Fig. 14. Close-up of a meniscate backfilled burrow of the *Taenidium* type. Scale bar is 1 cm.

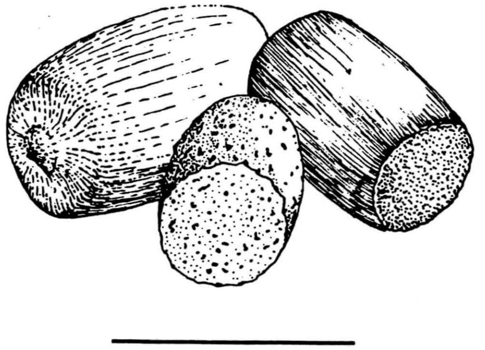

Fig. 15. Drawing from photomicrograph of faecal pellets. Scale bar is 1 mm.

filled with distinctive meniscae which in the Homeb examples are disc-shaped. The burrows are 5–15 mm in diameter being in the same size range as *Skolithos*. Burrows which have pellets in the meniscae are best ascribed to the ichnospecies *Taenidium satanassi*.

The ichnogenus *Taenidium* was revised by D'Alessandro and Bromley (1987), whose systematics are adopted in this paper. It is believed that the *Taenidium* burrower ingested wet sediment as it moved through the substrate and used the expelled pelleted and non-pelleted faeces as backfill. In many cases the mucus-coated faecal matter provides a favourable growth medium for bacteria or other microorganisms which serve as food for another level of deposit feeders. Many organisms of this type have elaborate avoidance behaviours to prevent them re-processing sediment which has already been ingested and excreted by them, or by another of their kind (Smith and Crimes, 1983).

4. Pellets and associated structures (Figs. 15, 17)

Pellet-filled chambers occur within the Homeb sediments. They are irregularly shaped and the largest observed was 600 mm × 20 mm. Some of the chambers are associated with burrows but they more commonly cross-cut other traces. The pellets in any chamber are remarkably uniform in size, being bacillus-shaped, often with a small conical peak at one end. They are commonly less than 1 mm long, but rarely larger pellets are found attaining a size of 4.3 mm long by 3 mm in diameter.

The sizes and shapes of the Homeb pellets resemble the faecal and pseudo-faecal pellets which are generated by fiddler crabs on modern tidal flats. Modern ants and termites exhibit similar behaviour and we consider it likely that these pellets were made by terrestrial arthropods. Ants 'pelletise' sediment to enable the workers to carry larger fragments outside the nest. However, underground storage could also be a useful behaviour pattern as it might help to conceal the ant colony from predators. Thus the pellet-filled chambers may have been made by terrestrial arthropods after the sediment had dried out and compacted.

Pellets are often found in *Taenidium* burrows. Other burrows are lined with pellets giving them a pitted external surface. This makes them technically small *Ophiomorpha* (Merrill, 1984) which are normally indicative of a shallow marine palaeoenvironment (Seilacher, 1967), but following Bromley and Asgaard's (1991) lead we use both these ichnogenera without any marine or non-marine connotation. Some of the pellet-walled trace fossils from diamondiferous deposits in Namaqualand are unequivocally made by terrestrial organisms, probably termites, and one of us (TRM) has an excellent laboratory specimen of a modern pelleted termite tube which is essentially similar to the Homeb examples, except that it is not filled with sediment.

Some pellets are robust enough to survive transportation in traction currents and have been observed in climbing ripple toesets. These may be surface-produced pellets, or they may have been laid down just below the surface and exhumed by current scour. It is also likely that pellets which are not immediately eaten or otherwise disturbed are pre-disposed to early cementation, as is the case on modern tidal flats and carbonate-rich environments where pellets made by various types of burrowing invertebrates are common sedimentary particles. The Homeb Silt pellets may well have hardened by desiccation and as such could have been moved considerable distances by currents.

Some of the larger pellet-filled burrows could be interpreted as possible brood structures, reminiscent of similar burrow modifications documented for callianassids (Curran, 1976). It is concluded that these pellets were probably made by terrestrial arthropods, such as ants or termites, that colonised the alluvium after it had dried out.

5. Rhizocretions—Chondrites-like trace fossils (Fig. 18)

Root tubules or rhizocretions occur as 1–1.5 mm diameter hollow tubes with a flattened cylindrical cross-section; they characteristically display an opposing branching pattern typical of fibrous rooted grasses. Some tubes are straight, up to 75 mm long with complex branching patterns. Unlike the burrows, which are usually friable and similar in colour to the sediment, the tube walls are made of a brittle white calcareous material. Some tubes are encased in a sandy coating and tend to be rounder and less compressed.

The Homeb rhizocretions are associated with *Chondrites*-like trace fossils, but it is difficult to say if these are part of the plant rootlet system, or if they are related to the tunnelling activities of termites. We initially favoured the latter interpretation as these trace fossils have consistently flattened cross-sections, and termite burrows in the modern Namib environment are similar. We found no evidence of plant tissue in any of the thousands of specimens which we looked at in the field. On reflection, we believe that these trace fossils were possibly "joint ventures" with both plant and animal components. The animals (ants or termites) possibly used the rootlet tubules as convenient pathways into the soil.

6. Termitichnus (cf. Bown, 1982; Figs. 16, 19)

Type 1: *Termitichnus* (*Hodotermes*-type). This is a vertical tube with a complex lower network of chambers. These are intimately associated with vertical rhizocretions. We believe that they represent pathways from the surface to the underground dwelling, and that the plant roots were used as a convenient route.

Type 2: *Termitichnus* (*Psammotermes*-type). This is characterised by a network of interconnecting flattened tunnels lined with calcareous laminae. We think that the *Chondrites*-like tubules are broken fragments of this type of burrow system.

Fig. 16. *Termitichnus* type 1 burrows being exhumed by wind-etching from sandy siltstone of the Homeb Silt Formation. Scale in cm.

7. Arthropod trackways (Fig. 13)

Monomorphichnus-like tracks that are formed from a series of small arcuate C- or V-shaped prod marks lining a continuous, sinuous, 5 mm wide groove. On a flat surface, two opposing rows of marks occur in groups of six pairs with each prod mark being 2 mm in length. These are interpreted as furrowing and walking traces of aquatic arthropods, resembling modern traces made by tiger beetles and their larvae. We interpret these distinctive markings as the bedding surface tracks of the *Taenidium* and *Skolithos* trace makers.

8. Fodinichnia indet. (Fig. 13)

This is a sinuous invertebrate trail apparently originating, or terminating, at a single point. It comprises two to five "loops", forming a continuous narrow groove 1 mm wide by 0.5 mm deep. The edges of the groove are slightly raised above the siltstone surface.

9. Vertebrate trackways

A 30 m long trackway of bovid hoof impressions occurs on the mudcracked surface of a massive siltstone in the upper part of the Homeb succession (Fig. 4). We also observed hoofprints in vertical sections (Fig. 9), which show distinctive U-shaped deformation of rapidly alternating beds of fine sediment.

Discussion

There are relatively few studies of the ichnology of flash-flood fluvial sediments that are comparable to the Homeb Silts. These include examples from Tertiary deposits of Nebraska (Ratcliffe and Fagerstrom, 1980), Egypt (Bown, 1982), and the Bighorn basin of Wyoming (Bown and Kraus, 1987). A suite of trace fossils that are similar to those of the Homeb Silts occurs in fluvial overbank deposits of the Permo–Triassic Beaufort Group (Karoo Sequence), South Africa, where they are associated with vertebrate fossils of the *Lystrosaurus / Procolophon* Assemblage Zone (Lawes, 1983; SACS, 1993). This assemblage is dominated by clay-filled vertical tubes (*Skolithos*), which have a surface expression of either small depressions or domes, as noted in the Homeb outcrops. *Taenidium* is also known from these localities, and burrows with sculpted walls, which may be assigned to the genus *Scoyenia*, are common.

It is striking that trace fossils are extremely rare in the fine-grained sediments of the modern Kuiseb River at Homeb. Unpublished observations by one of us (TRM) of potential trace fossils being formed in modern fluvial deposits in Natal show that most of the traces are made by organisms which exploit the 'plastic' mud veneer which drapes sandy sediment. These mud veneers are laid down during waning flow conditions as miniature fining-upward sequences. It is also noteworthy that trace makers caught in the act are mostly beetles and beetle larvae, spiders, earwigs and crickets. The crickets and the beetle larvae make the primary burrows, and the adult beetles and spiders are predators that merely occupy tunnels dug by other organisms. The scale of the modern tunnels varies from one or two millimetres in diameter, to almost ten millimetres. The sinuous tunnels, formed just under the sediment surface (*Tunnelfahrten* of Hantzschel, 1975), are defined on surface by a linear mound of polygonal cracks.

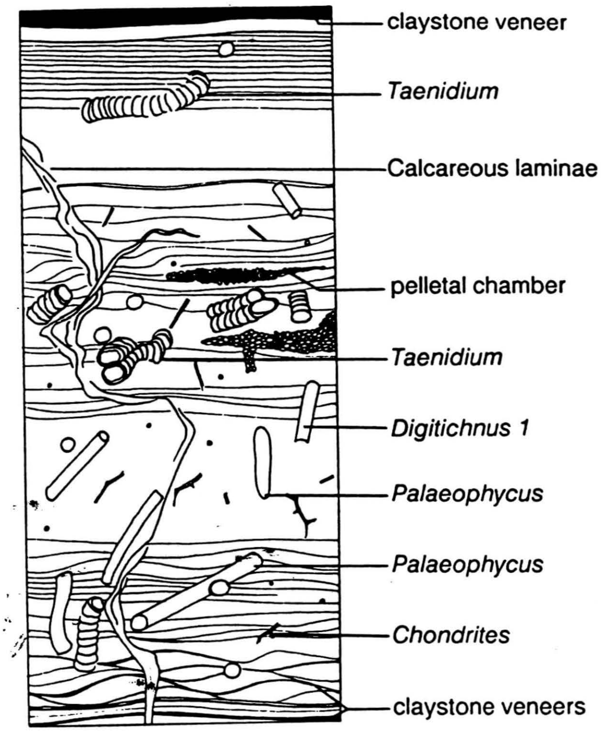

Fig. 17. Sedimentary structures and trace fossils seen in detail *1* from the cliff section of Fig. 6. Note the two pellet-filled chambers interpreted as having been built by ants or termites. Panel size 40 × 17 cm.

Ichnofacies description and interpretation

There are two distinct superimposed ichnofacies in the study section. The first is common throughout the section and is here termed the Arenicolites ichnofacies (Bromley and Asgaard, 1991; Figs. 17, 18, 19). This ichnofacies is dominated by unlined meniscate burrows of *Skolithos*, *Taenidium* and *Planolites* types. They appear to have been formed in soft sediment which was covered by flood water long enough for it to be colonised by aquatic substrate-ingesting opportunists. In many cases this ichnofacies has been disrupted by the burrowing activity of terrestrial arthropods after the floodwaters had drained and the substrate had dried out. These later burrows are part of the *Termitichnus* ichnofacies and are characterised by lined tubes and pellet-filled chambers which we interpret as having been made by ants and termites. It includes the two *Termitichnus* types described above, and the *Chondrites*-like traces found in close association with them.

We here formally propose that the *Termitichnus* ichnofacies be established as a distinct terrestrial ichnofacies, possibly considered as a subset of the archetypical Seilacherian *Scoyenia* ichnofacies (Seilacher, 1967). We make this proposal mindful of Bromley and Asgaard's (1991) suggestion that the *Scoyenia* ichnofacies be discarded, but further recommend that to resolve this nomenclatorial problem, the *Scoyenia* ichnofacies may be considered as a higher category of ichnotaxon (a "megaichnofacies" of Bromley, 1990). This may be subdivided into a number of distinct ichnofacies from different terrestrial environments. In Africa we have seen fairly distinctive ichnofacies from lacustrine, floodplain and terrestrial woodground environments: we have also observed their modern equivalents. We believe that it ought to be possible to differentiate floodplains from different climatic regimes on the basis of their trace fossils. The trace fossils described from other floodplains (Nebraska—Ratcliffe and Fagerstrom, 1980; Egypt—Bown, 1982; Bighorn basin, Wyoming—Bown and Kraus, 1987) are not precisely the same as these Namibian examples, so we feel that it would be best to leave some latitude for further refinement of floodplain ichnofacies.

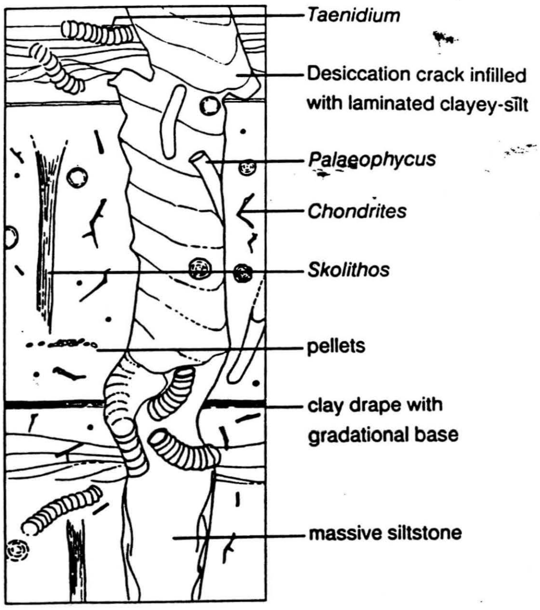

Fig. 18. Sedimentary structures and trace fossils seen in detail *2* from the cliff section of Fig. 6. Note the downward deflected laminae in the (? aeolian) sandstone infilling the upper part of the desiccation crack. Panel size 40 × 17 cm.

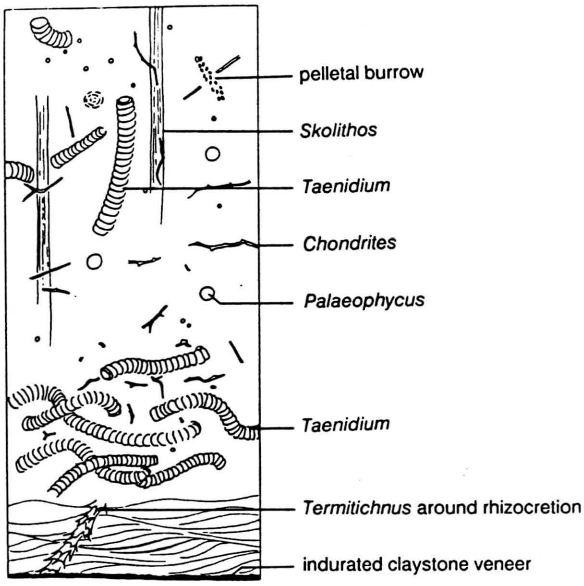

Fig. 19. Sedimentary structures and trace fossils seen in detail *3* from the cliff section of Fig. 6. Here there appears to be a "horizon" of horizontally orientated *Taenidium* burrows. Panel size 40 × 17 cm.

Ichnofabric tiering. The succession of ichnofacies supports the sedimentological evidence that fine-grained alluvium was laid down episodically in side valleys of the Kuiseb canyon. The ichnofabrics appear to show an overprinting or tiering of the ichnofossils. Initially water-dwelling organisms invaded the newly deposited alluvium when it was still soft and plastic resulting in the *Taenidium* ichnofacies. After emergence and drying out of the floodplain, terrestrial arthropods (possibly ants or termites) exploited the substrate forming the *Termitichnus* ichnofacies. This pattern was repeated time and again after each successive flood causing the ichnofabric to obliterate the primary bedding structures and in parts comprehensively homogenise the sediment. In the modern Namib sand sea a similar succession may be observed in the playa deposits of Sossus and Tsondab vleis.

Palaeoenvironmental interpretation of the Homeb Silt Formation

The Homeb sediments are vertically accreted as stacked flood units. Each comprises a basal scour surface, overlain by 3 to 30 cm of silt, which is horizontally laminated at the base, and passes upward into climbing ripple cross-lamination. In-phase and in-drift ripples both occur. The sequence is capped by a thin, but continuous veneer of clay which is sometimes desiccated and rarely displays raindrop impressions. These flood units record initial scour of the previously exposed floodplain surface but with minimal downcutting suggesting that the rising floodwaters in this area were unconfined rather than channelised. A similar sequence of sedimentary structures occurs in many fluvial overbank deposits especially on natural levees of mixed load rivers such as the Mississippi (Singh, 1972; Ray, 1976) and Indus (Sehgal and Stoops, 1972).

At peak discharge the Kuiseb channel expanded to fill the canyon and water depths increased to a level that allowed sediment-laden turbulent eddies to peel-off the mainstream flow and circulate into the embayments (McKee, 1938). Deposition of coarser bedload immediately downstream from the point of flow expansion probably formed a longitudinal bar behind which the reverse-circulating eddies would have been prevented from entering the mainstream again, thus effectively forming a closed backwater or slack-water pond (Patton et al., 1979). The present distribution pattern shows that the Homeb Silts were originally only deposited in gaps or embayments in the Kuiseb canyon walls where the floodwaters abruptly became unconfined and lost flow competence to transport their traction and suspension load. However, post-Homeb incision of the Kuiseb River has removed all trace of the coarser mainstream deposits that were originally laterally equivalent to the Homeb Silts.

On entering the embayment the eddies progressively slowed and lost flow competence resulting in the "dumping" of traction load and suspension fines through a continuous sequence of aggrading bedforms, leaving behind a layer of muddy silt containing sedimentary structures that closely resemble the "Bouma" turbidite sequence (Bouma, 1962). Baker (1973) made the same comparison when interpreting rhythmites in the distal facies of side-valley terraces in the Tucannon valley, Washington and attributed their formation to the superposition of bedforms created under waning density flows as traction transport gave way to suspension settling.

It is tempting to interpret the "thinning upward" sequences of beds in the Homeb Silts as the transition from mainstream-dominated discharge to tributary-sourced discharge. However, the palaeocurrent indicators in the upper alternations show strong up-valley trends that can only have been flowing from the Kuiseb River. Thus it appears that the upward-thinning sequences of flood units were initiated by one or more major flood surges that deposited amalgamated beds of muddy siltstone. This was followed by an extended period of "normal" flash-flood sedimentation resulting in a series of smaller flood units interspersed with aeolian and colluvial deposits.

Sheetwash breccias composed of locally derived bedrock fragments in a coarse sandstone matrix occur throughout the Homeb succession, commonly in association with aeolian deposits. In the type locality the breccias are more abundant above an embayment-wide erosion surface that lies some 11 m below the topmost strata. This unconformity possibly represents a single major flood event but the markedly thicker flood units in the overlying beds suggest that the mainstream channel had migrated closer to the tributary mouth. Towards the top of the succession, the increased frequency of sheetflow fans and barchanoid dunes migrating over the alluvium possibly reflects a decrease in frequency of flooding.

Raindrop impressions and desiccation cracks testify to some sub-aerial exposure between flood events but the lack of visible pedogenic modification of the alluvium, apart from root channels, suggests that the soils were extremely immature and that the periodicity of major floods was less than 50 years, perhaps in the order of 20–30 years and minor flash floods were possibly an annual event.

The ichnofossils support the interpretation of sedimentary features in the Homeb Silts and tell a tale of successive flood events separated by extended periods of desiccation. Compared to the impoverished ichnofauna of the modern Kuiseb River, this ancient fauna was a much more diverse assemblage, suggesting that the climate was less harsh and arid when these sediments accumulated. The seasonal rainfall may have been more reliable, allowing those organisms with resting stages and those which use arrested embryonic development to recolonise the same areas over and over again. With the onset of the modern hyperarid phase, flooding of the Kuiseb River has become less frequent and more unpredictable so that only the hardiest of invertebrates survive.

Summary

Three stages in the generation of the Homeb Silt terraces at Homeb are illustrated in Fig. 20. This is in effect a summary of the "Namib Desert Phase" of Ward and Corbett (1990) that affected the entire West Coast following the establishment of the cold-water Benguela upwelling system in the Late Miocene.

Stage 1

The Kuiseb canyon was cut by the westward flowing Kuiseb River in response to epeirogenic crustal uplift during the Pliocene to Early Pleistocene (Fig. 20, 1). During the earliest aggradational episode the river had a braided character as evidenced by the remnant gravel bars with interbedded aeolianites known as the Oswater Conglomerate Formation (Ward, 1987).

Stage 2

Following several cycles of aggradation and erosion the river underwent an extended period of alluviation, during the Middle to Late Pleistocene, resulting in the Homeb Silt Formation. Whether this aggradation was in response to crustal downwarping (eustatic) or increased discharge (climatic) is not known but the increase in rate of alluviation without a corresponding increase in grain size suggests a source area control. This is most likely to have been caused by an extended period of increased rainfall in the Khomas highlands, the catchment of the Kuiseb

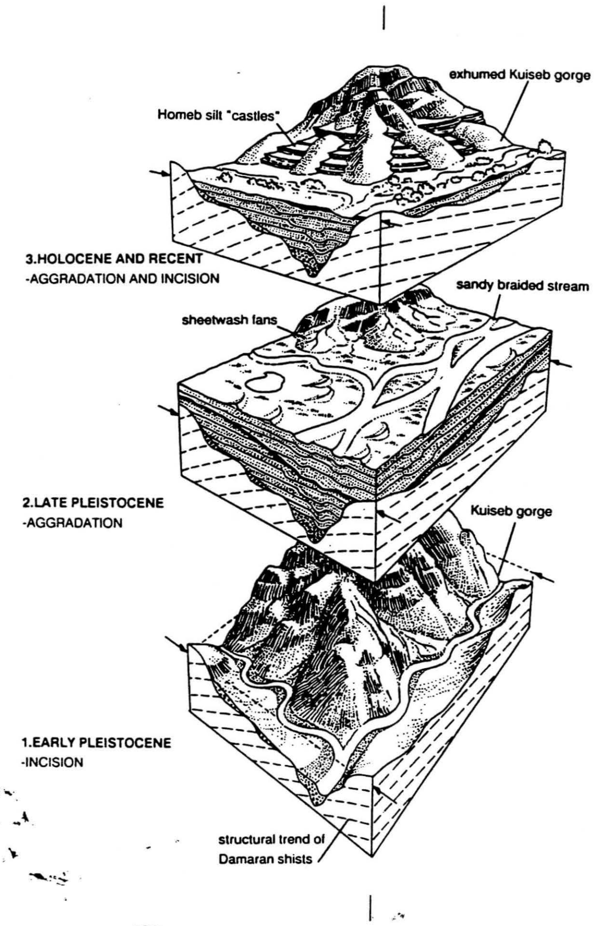

Fig. 20. Reconstruction of the depositional history of the Homeb Silt Formation at Homeb in the Kuiseb River canyon. *Stage 1*: downcutting of the Kuiseb River during the Early Pleistocene to depths of 80–100 m into the bedrock planation surface. Deposition of the Oswater conglomerates and sandstones in the upper reaches of the canyon. *Stage 2*: deposition of alluvium in the canyon and tributary valleys during the Late Pleistocene mainly through successive flood episodes interspersed with periods of non-deposition and pedogenesis. This resulted in the accumulation of the Homeb Silt Formation. *Stage 3*: renewed incision of the Kuiseb River during the Holocene has removed most of the alluvium down to its present level and exhumed the original rock-walled canyon that was cut during stage 1. Remnants of the alluvium are still present in sheltered tributary valleys in the canyon section and probably still underlie the thin layer of recent sediments on the present river bed.

River, some 200 km to the northeast (Ward, 1987).

The sedimentology of the Homeb Silts indicates that they accumulated episodically as a result of successive back-flooding of the Kuiseb River into its tributary valleys. This resulted in the accumulation of stacked slack-water flood units in the tributary valleys and, although not exposed, laterally contiguous sandy channel deposits in the river course. Because the channel facies are not exposed, it is not possible to confirm the fluvial style at this time. However, the flash-flood hydrology and abundance of suspended load combined with widening of the valley as aggradation continued would probably have imposed a sandy-braided fluvial style on the Kuiseb River. Between major flood-sedimentation events which were possibly every 20–30 years, the semi-arid climatic conditions were moist enough for grasses to colonize the surface, resulting in incipient soil formation. At the same time small sheetwash fans prograded from the bounding rock walls and isolated aeolian dunes migrated across the alluvial flats from the Namib sand sea to the south.

Stage 3

Renewed downcutting of the Kuiseb River was possibly initiated by a lowering of base level during the early Holocene. The river eroded about 25 m into the floodplain, removing the bulk of the Homeb alluvium down to that level. This appears to have taken place in two episodes as evidenced by a small terrace in the incision profile (Vogel, 1982). Some of this alluvium was protected from complete removal in sheltered side valleys and is exposed today as the Homeb Silt Formation. The reconstruction shows a succession of intact Homeb sediments underlying the present valley floor which should contain the channel facies equivalent to the slack-water facies presently exposed.

The Homeb Silts confirm that the climate of the Namib has become much more arid over the past 20,000 years with suggestions that this aridity is linked to ocean current circulation, ancient El Nino effects, and other climatic perturbations. If we can improve our understanding of these events in the recent past, we may be better able to predict climatic changes in the immediate future.

Acknowledgements

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References

Allen, J.R.L., 1989. Fossil vertebrate tracks and indenter mechanics. J. Geol. Soc. London, 146: 600–602.

Baker, V.R., 1973. Palaeohydrology and sedimentology of Lake Missoula flooding in eastern Washington. Geol. Soc. Am., Spec. Pap., 144, 79 pp.

Bouma, A.H., 1962. Sedimentology of Some Flysch Deposits: A Graphic Approach to Facies Interpretation. Elsevier, Amsterdam, 168 pp.

Bown, T.M., 1982. Ichnofossils and rhizoliths of the nearshore fluvial Jebel Qatrani Formation (Oligocene), Fayum Province, Egypt. Palaeogeogr., Palaeoclimatol., Palaeoecol., 40: 255–309.

Bown, T.M. and Kraus, M., 1987. Integration of channel and floodplain suites, 1. Developmental sequence and lateral relations of alluvial paleosols. J. Sediment. Petrol., 57: 587–601.

Bromley, R.G., 1990. Trace Fossils: Biology and Taphonomy. Unwin Hyman, London, 280 pp.

Bromley, R.G. and Asgaard, U., 1979. Triassic freshwater ichnocoenoses from Carlsbad Fjord, East Greenland. Palaeogeogr., Palaeoclimatol., Palaeoecol., 28: 39–80.

Bromley, R.G. and Asgaard, U., 1991. Ichnofacies: a mixture of taphofacies and biofacies. Lethaia, 24: 153–163.

Butler, B.E., 1958. Deposition systems of the Riverine Plains of southeastern Australia in relation to soils. CSIRO Aust. Soil Publ., 10, 35 pp.

Byers, C.W., 1982. Geological significance of marine biogenic sedimentary structures. In: McCall, P.L. and Tevesz, M.J.S. (Editors) Animal–Sediment Relations. Plenum Press, New York, pp. 221–256.

Cody, R.D., 1991. Organo-crystalline interactions in evaporite systems: The effects of crystallization inhibition. J. Sediment. Petrol., 61: 704–718.

Cody, R.D. and Cody, A.M., 1988. Gypsum nucleation and crystal morphology in analog saline terrestrial environments. J. Sediment. Petrol., 58: 247–255.

Curran, H.A., 1976. A trace fossil brood structure of probable callianassid origin. J. Palaeontol., 50: 249–259.

D'Allesandro, A. and Bromley, R.G., 1987. Meniscate trace fossils and the *Muensteria – Taenidium* problem. Palaeontology, 30: 743–763.

Droser, M.D. and Bottjer, D.J., 1986. A semiquantitative field classification of ichnofabric. J. Sediment. Petrol., 56: 558–559.

Droser, M.D. and Bottjer, D.J., 1989. Ichnofabric of sandstones deposited in high-energy nearshore environments: measurement and utilization. Palaios, 4: 598–604.

Ekdale, A.A., 1988. Pitfalls of bathymetric interpretations based on trace fossil assemblages. Palaios, 3: 464–472.

Ekdale, A.A. and Picard, M.D., 1985. Trace fossils in a Jurassic aeolianite, Entrada Sandstone, Utah, USA. In: H.A. Curran (Editor), Biogenic Structures: Their Use in Interpreting Depositional Environments. SEPM Spec. Publ., 35: 3–12.

Ekdale, A.A., Bromley, R.G. and Pemberton, S.G., 1984. Ichnology. The use of trace fossils in sedimentology and stratigraphy. Soc. Econ. Paleontol. Mineral. Short Course, 15, 317 pp.

Frey, R.W., Pemberton, S.G. and Fagerstrom, J.A., 1984. Morphological, ethological and environmental significance of the ichnogenera *Scoyenia* and *Ancorichnus*. J. Palaeontol., 58: 511–529.

Frostick, L.E. and Reid, I., 1977. The origin of horizontal laminae in ephemeral stream channel-fill. Sedimentology, 24: 1–9.

Goudie, A., 1972. Climate, weathering, crust formation, dunes and fluvial features of the Central Namib Desert near Gobabeb, South West Africa. Madoqua, II (1): 15–31.

Hantzschel, W., 1975. Trace fossils and problematica. In: C. Teichert (Editor), Treatise on Invertebrate Palaeontology, 2nd ed. Geological Society of America, Kansas Univ. Press, 269 pp.

Klappa, C.F., 1980. Rhizoliths in terrestrial carbonates—classification, recognition, genesis and significance. Sedimentology, 27: 613–629.

Lawes, M., 1983. A Study on the Lithology, Sedimentology and Taphonomy of Upper Estcourt Formation Deposits, Beaufort Group, at the De Hoek Fossil Site, Draycott, Natal. Unpubl. Hons. Dissert., Univ. Natal, Pietermaritzburg, 68 pp.

Loope, D.B., 1986. Recognising and utilizing vertebrate tracks in cross-section: Cenozoic hoofprints from Nebraska. Palaios, 1: 141–151.

Marker, M.E., 1977. Aspects of the geomorphology of the Kuiseb River, South West Africa. Madoqua, 10 (2): 199–206.

Marker, M.E. and Muller, D., 1978. Relict vlei silt of the middle Kuiseb valley, South West Africa. Madoqua, 11 (2): 151–162.

Mason, T.R., Stanistreet, I.G. and Taverner-Smith, R., 1983. Spiral trace fossils from the Permian Ecca Group of Zululand. Lethaia, 16: 241–247.

McKee, E.D., 1938. Original structures in Colorado River flood deposits of the Grand Canyon. J. Sediment. Petrol., 8: 77–83.

McKee, E.D. Crosby, E.J. and Berryhill, H.L., 1967. Flood deposits, Bijou Creek, Colorado, June 1985. J. Sediment. Petrol., 37: 829–851.

Merrill, R.D., 1984. *Ophiomorpha* and other trace fossils from the Eocene Ione Formation, California. J. Palaeontol., 58: 542–549.

Netterberg, F., 1980. Geology of Southern African calcretes, 1. Terminology, description, macrofeatures, and classification. Trans. Geol. Soc. S. Afr., 83: 255–283.

Ollier, C.D., 1977. Outline geological and geomorphological history of the Central Namib Desert. Madoqua, 10 (3): 207–212.

Osgood, R.G., 1970. The trace fossils of the Cincinnati area. Palaeontogr. Am., 6, 281–444.

Patton, P.C., Baker, V.R. and Kochel, R.C., 1979. Slack-water deposits: a geomorphic technique for the interpretation of fluvial paleohydrology. In: D.D. Rhodes and G.P. Williams (Editors), Adjustments of the Fluvial System. Proc. 10th Geomorphology Symp., Binghampton, New York, pp. 225–254.

Ratcliffe, B.C. and Fagerstrom, J.A., 1980. Invertebrate lebensspuren of Holocene Floodplains: their morphology, origin and palaeoecological significance. J. Palaeontol., 54: 614–630.

Ray, P.K., 1976. Structure and sedimentological history of overbank deposits of a Mississippi River point bar. J. Sediment. Petrol., 46: 788–801.

Rust, U. and Weinke, F., 1974. Studies on gramadulla formation in the middle part of the Kuiseb River, South West Africa. Madoqua, II (3): 5–15.

Rust, U. and Weinke, F., 1980. A reinvestigation of some aspects of the evolution of the Kuiseb River valley upstream of Gobabeb, South West Africa. Madoqua, 12 (3): 163–173.

Scholtz, H., 1972. The soils of the central Namib Desert with special reference to the soils in the vicinity of Gobabeb. Madoqua, 11 (1): 33–51.

Seely, M.K. and Sandelowsky, B.H., 1974. Dating the regression of a river's end-point. S. Afr. Archaeol. Soc. Goodwin Ser., 2: 61–64.

Sehgal, J.L. and Stoops, G., 1972. Pedogenic calcite accumulation in arid and semi-arid regions of the Indo-Gangetic alluvial plain of erstwhile Punjab (India)—their morphology and origin. Geoderma, 8: 59–72.

Seilacher, A., 1967. Bathymetry of trace fossils. Mar. Geol., 5: 413–428.

Seilacher, A., 1978. Use of trace fossil assemblages for recognising depositional environments. In: P.B. Basan (Editor), Trace Fossil Concepts. SEPM Short Course, 5: 167–181.

Singh, I.B., 1972. On the bedding in the natural levee and point bar deposits of the Gomti River, Uttar Pradesh, India. Sediment. Geol., 7: 309–317.

Smith, A.B. and Crimes, P., 1983. Trace fossils formed by heart urchins—a study of Scolicia and related traces. Lethaia, 16: 79–92.

South African Commission for Stratigraphy, 1993. The Biostratigraphy of the Beaufort Group, Karoo Sequence, South Africa. S.A.C.S., Government Printer, Pretoria, in press.

Turner, B.R., Stanistreet, I.G. and Whateley, M.K.G., 1981. Trace fossils and palaeoenvironments in the Ecca Group of the Nongoma Graben, northern Zululand, South Africa. Palaeogeogr., Palaeoclimatol., Palaeoecol., 36: 113–123.

Vogel, J.C., 1982. The age of the Kuiseb River silt terrace at Homeb. Palaeoecol. Afr., 15: 201–209.

Ward, J.D., 1987. The Cenozoic succession in the Kuiseb Valley, central Namib Desert. Mem. Geol. Surv. Namibia, 9, 123 pp.

Ward, J.D. and Corbett, I., 1990. Towards an age for the Namib. In: M.K. Seely (Editor) Namib Ecology: 25 years of Namib research. Transvaal Mus. Monogr., 7: 17–26.