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Mass and hyperconcentrated flow deposits record dune damming and catastrophic breakthrough of ephemeral rivers, Skeleton Coast Erg, Namibia

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Abstract

Channel-shaped deposits of well sorted sand with only 2–4% fine-grained material, being either massive and structureless or upward fining with basal lag, are found interbedded with aeolian sand in the Skeleton Coast Erg, Namibia. Detailed analyses of the channel-shaped deposits suggest that they are formed as hyperconcentrated flows within the erg. Grain-size analysis and whole rock geochemical modeling revealed that some of the fluvial sediments contain up to 70% aeolian sand, interpreted as a result of dune collapse into the fluvial system. In certain cases, this instantaneous supply of sand resulted in generation of sandy mass flows with laminar flow behaviour. The presence of smectite as dominant clay mineral proved to be of crucial importance in formation of mass flow deposits. These mass flows had no erosional capacity, and drape the palaeotopography. They are comparable to those generated by catastrophic collapse of dunes, described in the literature. This paper suggests that all these deposits should be termed *intra-erg mass flows*, as several of them carry little, if any debris. Based on their origin, intra-erg mass flows can be divided into two groups:

(1) Attached intra-erg mass flows, which are formed and found attached to the dune that sourced the flow;
(2) Detached intra-erg mass flows, which are not found adjacent to the dune sourcing the flow, and often carry material sourced outside the dune field.

A five-stage model is proposed, involving dune damming to explain the observed deposits and the degree of reworking. When the flood basin behind the erg overtops the threshold area, water pours into the erg, giving rise to a complex fluvio-aeolian setting. The setting in the Skeleton Coast erg is comparable to recent as well as ancient settings, and reveals valuable information for reservoir characterization and hazard assessment.

Keywords: Namibia; Fluvio-aeolian interaction; Ephemeral rivers; Dune damming; Hyperconcentrated flows; Intra-erg mass flows

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1. Introduction

1.1. Hyperconcentrated flows

The words often applied to some of the historic Colorado River floods 'too thin to plow and too thick to drink' (Beverage and Culbertson, 1964) portray in a broad sense the flow characteristics of hyperconcentrated flows, which include a wide range of transport processes characterized by a turbulent transitional-to-laminar support mechanism (Costa, 1988). Resulting deposits are typically massive or exhibit crude horizontal stratification with no scour and fill structures and range in grain size from pebble to sand-grade, commonly containing outsized cobbles and boulders.

In general, the terms "hyperconcentrated flow" or "hyperconcentrated flood flow" have been used to describe high-discharge flows of low water-to-sediment ratios in which turbulence is not the only sediment-support mechanism and in which deposition does not occur en masse (Smith, 1986; Pierson and Costa, 1987). Classification schemes of subaerial sediment–water flows have been proposed by several authors (Lowe, 1982; Costa, 1987; Coussot and Meunier, 1996), based on sediment concentration and flow velocities. In this study, the classification and terminology of Pierson and Costa (1987) has been applied (Fig. 1). The principal rheology of the flows is transitional between true Newtonian fluid type flow behaviour of "normal" stream flows and

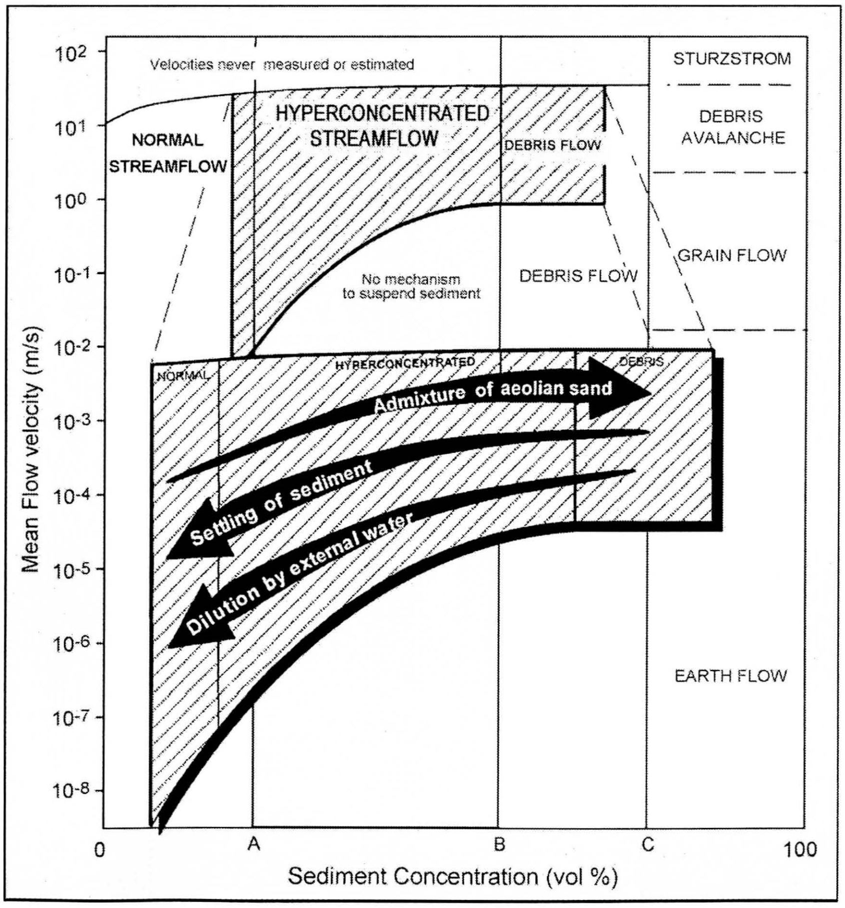

Fig. 1. Rheologic classification of "normal" stream flows, hyperconcentrated stream flows, and debris flows (modified from Pierson and Costa, 1987).

non-Newtonian or plastic flow as expressed by debris flows (cf. Smith, 1986; Pierson and Costa, 1987; Sohn et al., 1999). Hyperconcentrated flow deposits may thus record evidence of both matrix-supported debris flows and multiple phase stream flow behaviour, where coarser sediment, fines and water travel at different velocities. The transition between each flow type can be abrupt (Coussot and Meunier, 1996) or gradational (Sohn et al., 1999) where flow properties change due to downstream segregation of coarser grain sizes in highly concentrated debris flows, or due to the dilution of debris flows by mixing with water or less concentrated flows (Smith and Lowe, 1991). The latter can result in complex flow architectures with hyperconcentrated flows constituting the body and/or tail of a composite sediment-laden flow (Pierson and Scott, 1985; Smith, 1986; Sohn et al., 1999). Fields separating different flow types in Fig. 1 might therefore vary, dependent upon grain size, sorting, and cohesivity of flows and should be understood as proxies.

Hyperconcentrated flows have been described from a range of environments including alluvial fans, rivers, volcanic and glacial settings where high sediment concentrations are favoured by abundant sediment supply and high magnitude flow events. Examples of hyperconcentrated flow mobilizations comprise caldera lake outburts (Manville et al., 1999), remobilization of airfall tephra in volcanic settings (e.g. Smith, 1986; Lirer et al., 2001), and landslides triggered by exceptional rainfalls in mountainous and/or arid regions (e.g. Pierson and Costa, 1987; Sohn et al., 1999). In this paper, we extend the formation and the depositional setting of hyperconcentrated flows to the sand desert environment of the modern northern Namib Desert—a scenario which is not yet described in detail nor fully understood in the sedimentological literature. The overall structureless to faintly bedded nature of hyperconcentrated flow deposits suggests these also as a further explanation for the formation of massive sandbodies. Such structureless homogenous sandy deposits have been recognized in various modern and ancient dune fields and were interpreted to originate from cohesive, sandy debris flows (Jones and Blakey, 1997), mass wasting (Loope et al., 1999), or sediment-gravity flows (Benan and Kocurek, 2000).

1.2. Northern Namib fluvio-aeolian systems

The northern Namib Desert includes the scenic Skeleton Coast erg, a sand desert ca. 150 km long and 6–20 km wide, aligned parallel to the Atlantic coast line of NW Namibia (Fig. 2A). The erg comprises simple and compound transverse and barchanoid dunes (Lancaster, 1982), which formed in response to the dominant onshore south to southwesterly coastal wind regime (Barnard, 1989). The erg starts in the south, east of Torra Bay, where single barchans (5–15 m high) merge together to form a ~ 7-km-wide belt. The dune belt ends where the Hoarusib River successfully prevents northward transport of aeolian sand, which accumulates on its southern side to a total height of 100 m and a up to a width of 22 km. However, some dunes cross the Hoarusib closer to the coast. The erg topography shows a gentle downwind rise from its onset in the south to its full development in north, with the total height representing cumulative result of the thickness of the aggradated sand and the moving dunes on top. Cross-sections of the southern part of the erg show considerable asymmetry with low barchanoid and sinuous crested dune forms in the eastern part (< 20 m high) but a high, laterally continuous dune wall made up of composite transverse dunes (up to 30 m high) at its windward western edge (Fig. 3).

Several westward flowing ephemeral rivers attempt to traverse the Skeleton Coast erg on their route towards the Atlantic Ocean. Of these, the Hoarusib River (Fig. 2B) flows most frequently, reaching the sea almost every year. In contrast, rivers such as the Uniab, Samanab, Hunkab and Hoanib (Fig. 2B) are effectively dammed by the dune barrier and rarely reach the sea, with the Hoanib forming the extensive Gui-Uin flood basin (Fig. 2) east of the erg (Stanistreet and Stollhofen, 2002).

The Uniab river is about 110 km long and drains a 4500 km^2 catchment area with an elevation range of 150–1635 m and only 2.3% receiving mean annual rainfall of >100 mm (Jacobson et al., 1995). It is the southernmost of the dune-dammed ephemeral rivers of the Skeleton Coast and presently maintains a well-established breakthrough corridor through the erg (Fig. 3). The satellite image also shows evidence of earlier breakthrough corridors, one about 2 km north and the other 2 and 4 km south of the presently active channel.

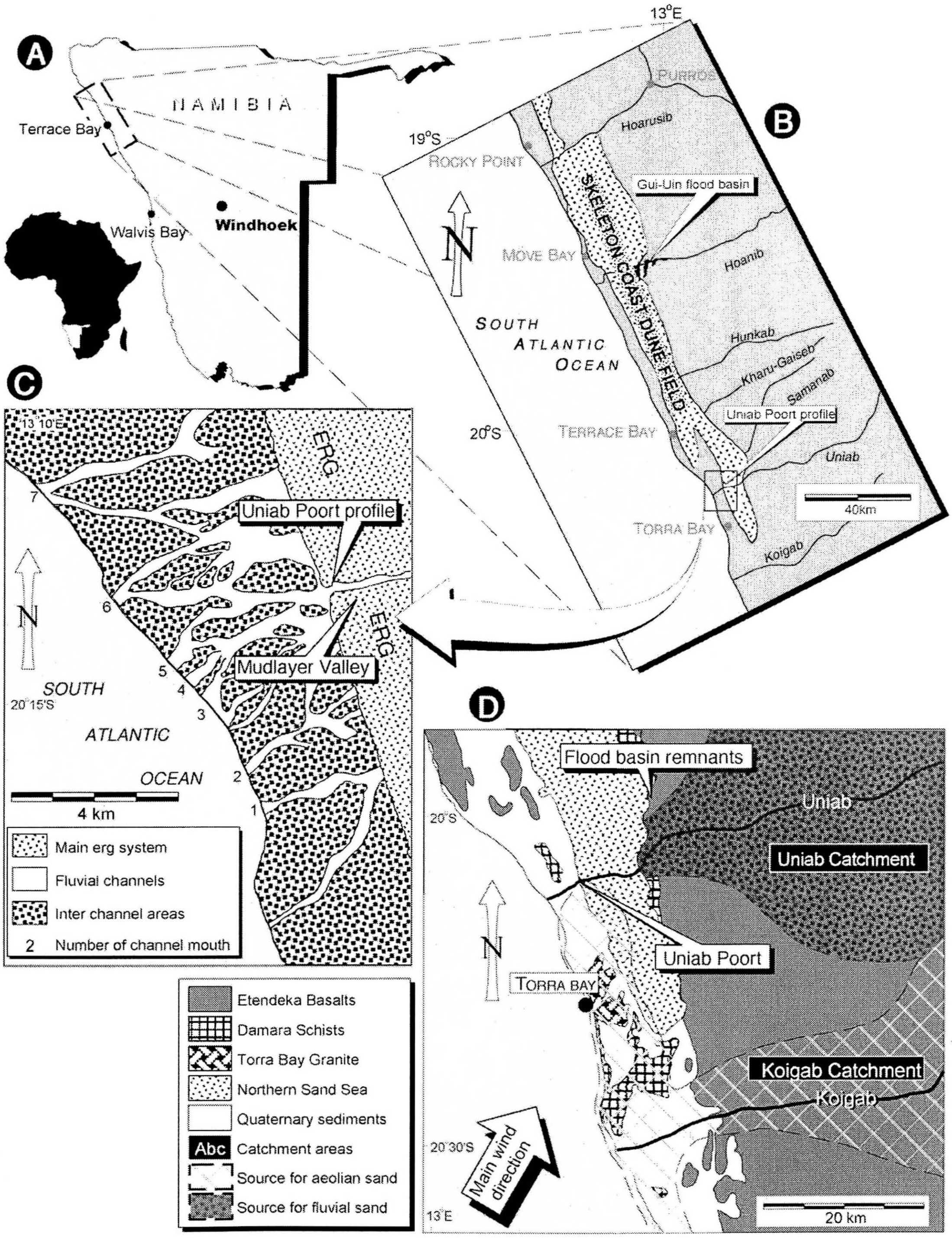

Fig. 2. (A) Location of the study area in NW Namibia, (B) location map of the Skeleton Coast erg, (C) a detailed map of the Uniab mouth area (only channels 3, 4 and 5 were active during the April 2000 flood), and (D) simplified geological map of the Uniab and Koigab area, with local basement rocks and fluvial and aeolian source areas highlighted.

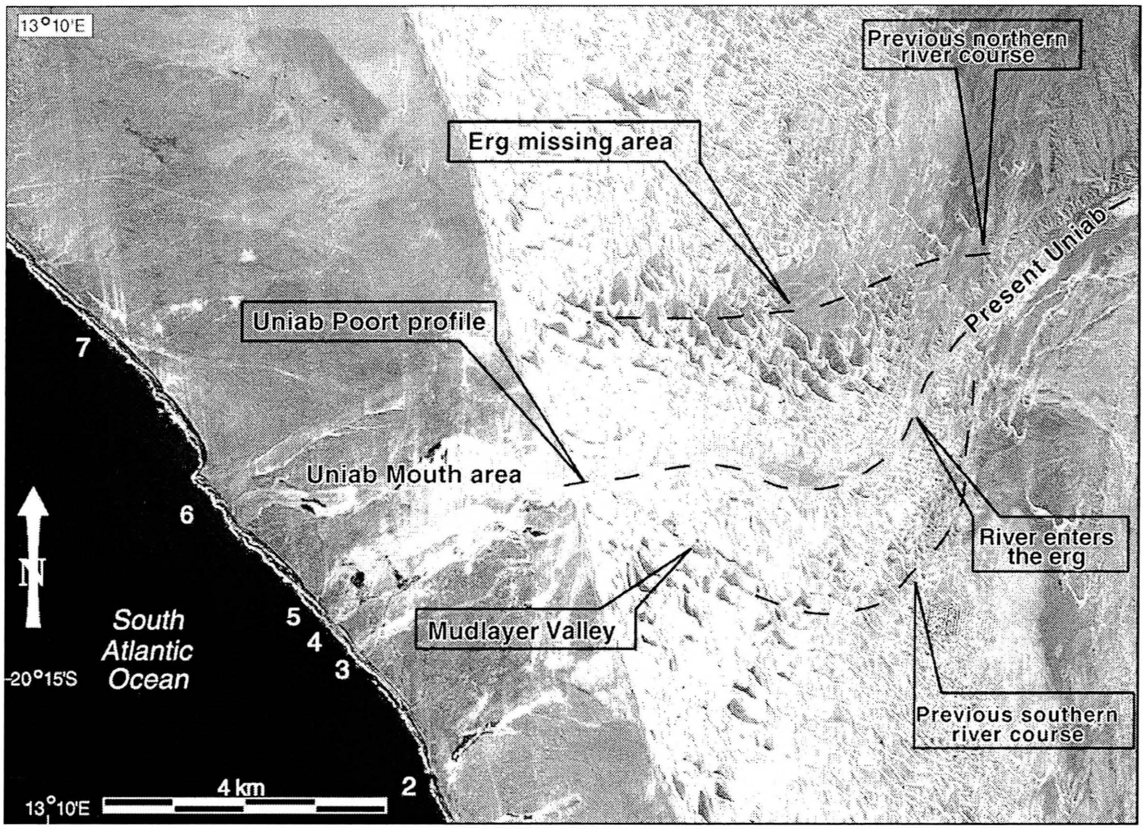

Fig. 3. Satellite image of the Skeleton Coast dune field with location of the Uniab Poort profile and Mudlayer Valley. Notice the simple and compound transverse and barchanoid dunes within the dune field and its pronounced W–E asymmetry.

Even if these earlier corridors are mostly buried by dune migration, belts of excavated interdunal mud-draped floodponds, originally filled from adjacent river channels (cf. Stanistreet and Stollhofen, 2002) do mark areas where successful breakthrough occurred in the past (Blümel et al., 2000). In addition, a remnant flushing of sand and mud onto the coastal deflation surface is obvious at the mouths of the earlier breakthrough corridors (Fig. 3). The width of these palaeobreakthrough corridors vary from 2700 m to the east down to 800 m to the west of the position where the prevailing SSW onshore winds favour enhanced healing on the windward side of the dune field.

1.3. Climatic setting

The Skeleton Coast is characterized by arid to hyper-arid conditions, with average annual precipitation below 50 mm (Jacobson et al., 1995). The virtual absence of rain in the coastal area is due to the low surface temperature of the South Atlantic, caused by extensive upwelling systems (Vogel, 1989), associated with the cold offshore Benguela Current. Thus, the main river catchment area lies 200–300 km inland from the Skeleton Coast where average annual rainfall reaches about 300–400 mm. However, if the dune barrier is intact, average rainfalls do not provide discharges high enough to enable the rivers to break through the dunes. Successful ephemeral river breakthroughs require exceptional rainfalls (Stanistreet and Stollhofen, 2002), often occurring as late-afternoon thunderstorms towards the end of the summer rainfall season. Such exceptional rainfalls are related to disturbances of the intertropical convergence zone. Some of these climatic anomalies may be equivalent to ENSO-type phenomena, well known from the western Pacific seabord (cf. Shannon et al., 1986).

During our field studies we were fortunate to record after-flood effects of the major April 1995 and April 2000 floods and the more minor March 1997 floods, lasting only 2–3 days each. The 1995 flood managed to breakthrough for the first time since 1982. Before, the Uniab flooded on a 9 years average during a period of 63 years. Longer-term climatic fluctuations have been recorded from the northern Namib, and wet and dry periods have alternated during the Namib Desert Phase, Miocene–present (Ward and Corbett, 1990). Several studies have looked in detail at the climatic changes during the last 100,000 years (Gingele, 1996; Eitel et al., 1999), suggesting that the northern Namib Sand Sea has experienced several periods with more humid conditions compared to the modern day climatic setting.

Little is known about shifts of the southern and northern margins of the Namib desert during the last 135,000 years. Heine (1998) states that phases more humid than today's climatic conditions occurred >25,000 to 19,000 ^{14}C years BP ago and about 10,000 to 8000 ^{14}C years BP, while lake sediments from Bullsport, southern Namibia, document wetter conditions after ca. 19,000 ^{14}C years BP (Heine, 1993). On a regional scale, OSL dating of samples from fossilized dune fields of the Namibian Caprivi Strip and western Zambia imply four periods of dune building, recording aridity during the time intervals of ca. 45,000–35,000, 30,000–20,000, 13,000–8,000 and 5000–3000 OSL years BP (O'Connor 1997; Heine, 1998). During the Last Glacial Maximum (LGM) 22,000–18,000 BP, the global temperature fell by about 5 K, which resulted in a 100% increase in wind velocities but also in a 30–40% drop in rainfall. Such conditions favoured aeolian dynamics in the Namib Sand Desert but also reduced the rivers' ability to break through the dune belt. Within the last 30,000 years, the LGM was the driest period in southwestern Africa (Blümel et al., 2000). Blümel et al. (2000) assume that the Skeleton Coast erg extended up to 1.5 km farther east during such dry episodes. Thus, the limits of the erg itself provide a monitoring base line for the record of climatic change.

2. The Uniab River system

2.1. Sediments and sources

The Uniab River is the southernmost of the Skeleton Coast rivers. It drains a 4500 km^2 catchment area, largely east of the erg which is more or less exclusively occupied by Early Cretaceous Etendeka basalts with interbedded quartz latites (Van-Zyl and Scheepers, 1991; Miller, 1988) (Fig. 2). Extensive parts of the catchment were affected by post-breakup uplift of the newly formed Namibian continental margin during early and late Cretaceous times, favouring considerable river incision. Average annual rainfall in the catchment varies from 0 to 125 mm but only 2.3% of the catchment area receives average annual rainfall of >100 mm. Consequently, the fluvial sand is sourced from the Etendeka volcanics.

The aeolian sediments are mainly supplied from deflation surfaces south–southwest of the Uniab, with a minor easterly component related to seasonal "bergwinds" (Lancaster, 1982). The derivation of aeolian sand is more ambiguous than the fluvial, as at least three source regions must be considered: (1) The beach area provides compositionally mature quartz sands. There is a strong longshore drift effect along the entire west coast of southern Africa and the mature quartz sand is likely to represent a complex mix of numerous sources; (2) the subaerial Koigab fan and mouth area, providing lithics-rich sands derived from the volcanic catchment of the Koigab River and (3) local basement rocks consisting of migmatised greywacke, Damara Schists, and garnet-bearing Torra Bay Granite (Miller, 1988).

Compositionally, the first is by far the most important, with minor components from the other sources admixed to varying degrees.

2.2. River morphology

The Uniab River classifies as an ephemeral braided stream originating in the Grootberg–Palmwag area and encounters the Skeleton Coast dune belt only 25 km east of the Atlantic coastline. The 110-km river course subdivides naturally into five segments. From upstream these are: (1) the Etendeka volcanics-dominated catchment area east of the dune field, (2) the dune entry area, (3) the dune break-

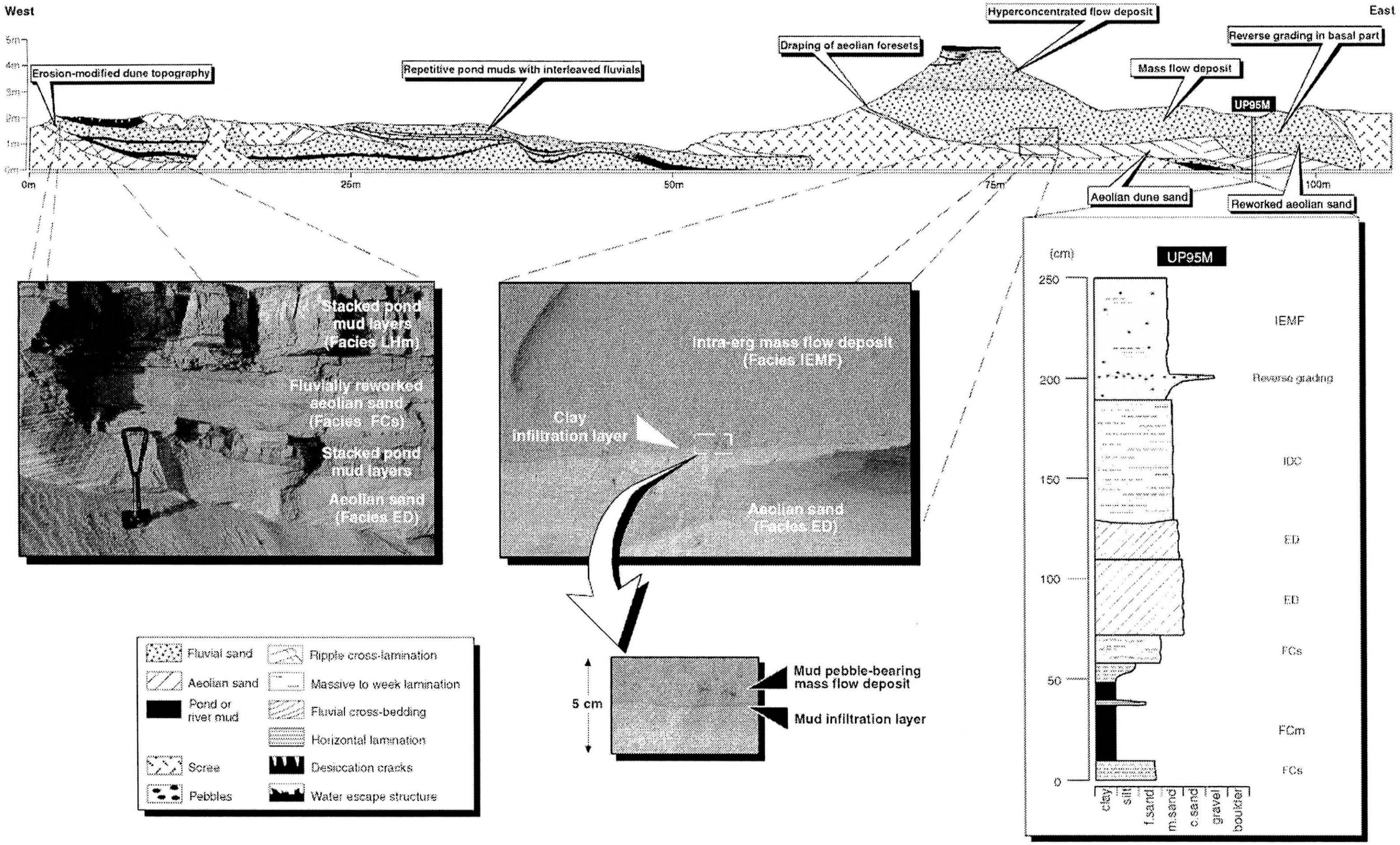

Fig. 4. Uniab Poort profile 0–105 m. Detailed line drawing of the examined outcrop and photos (left) of stacked interdune pond mud layers and (right) of intra-erg mass flow deposit (facies IEMF) with details of the mud infiltration layer and mud pebbles at its base highlighted. See Fig. 5 for facies summary table.

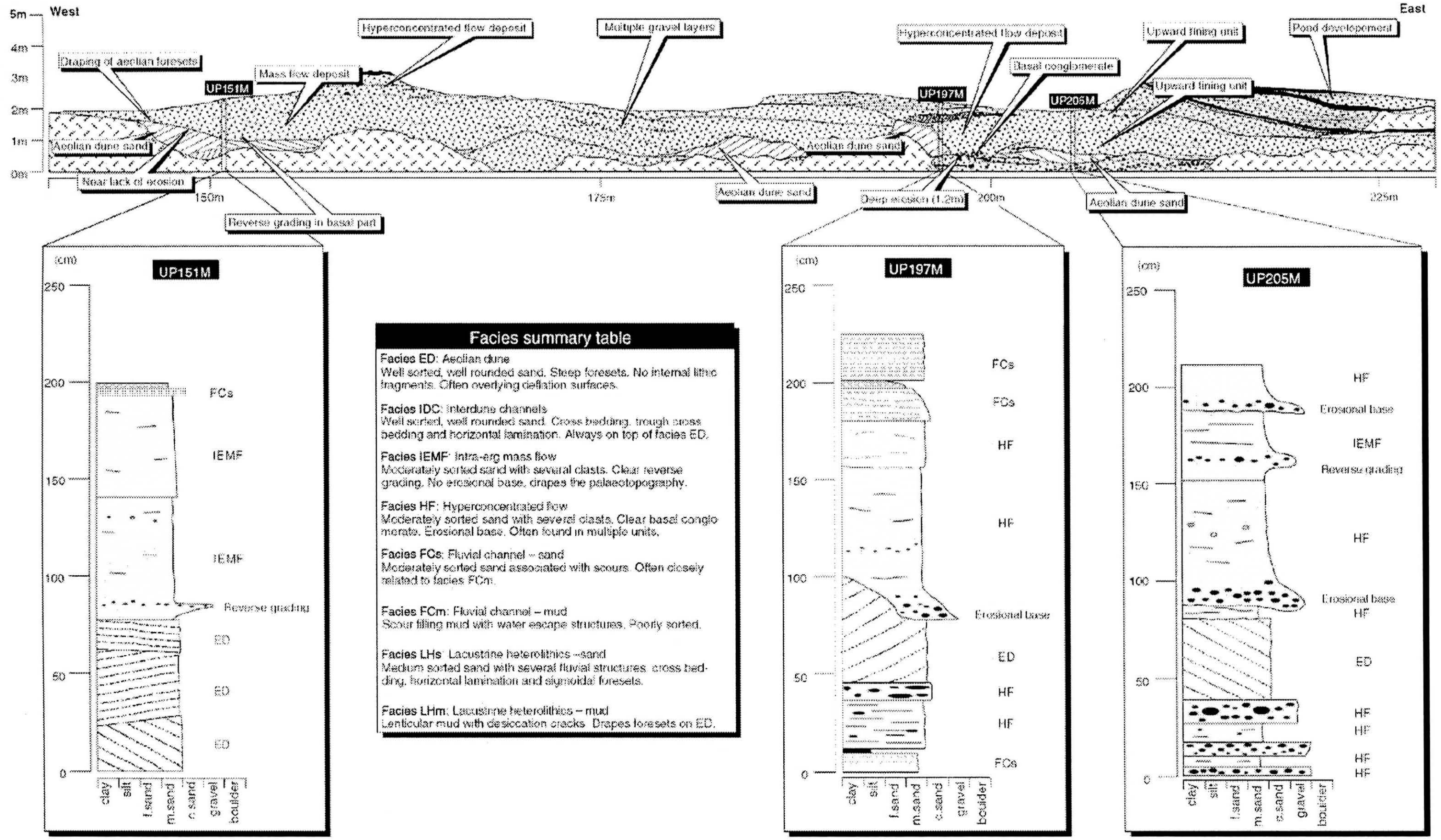

Fig. 5. Uniab Poort profile 140–230 m. Detailed line drawing of the examined outcrop. Sedimentological log at 151 m shows intra-erg mass flow facies IEMF draping aeolian facies ED. Sedimentological logs at 197 and 205 m are dominated by hyperconcentrated flow deposits (facies HF). Notice the basal lag in facies HF and the reverse grading in facies IEMF. See Fig. 4 for explanation of symbols.

through area, (4) the poort area; the term poort is here used to describe the exit pass where the river successfully transects the whole erg and enters the coastal plain, and (5) the Uniab mouth area, previously also termed the Uniab fan (Scheepers and Rust, 1999) (Figs. 2C and 3). Certainly the latter is one of the most spectacular geomorphological features along the entire river course. The mouth area is characterized by a prominent sea cliff some 18 km long and up to 35 m high which is dissected by nine deeply incised valleys (Fig. 3). The three central valleys host the river channels which were active during the April 2000 flood and expose the dominantly basaltic and quartzlatitic gravel deposits of the Uniabmond Formation (Fig. 2C). This forms a bahada-type gravel body which can be traced 0.5 km inland towards a palaeo-seacliff the base of which is 9.5 m above present sea level.

Fig. 3 illustrates where the Uniab passed through the erg during early April 1995 with the presently active channel clearly marked by aeolian sand and mud flushed out of the erg and distributed over the coastal plain deflation surface. Also obvious are earlier breakthrough corridors to either side (ca. 2 km) of the active channel. Remnant patches of thin plane-laminated silt deposits are spread east of the dune entry area and were interpreted to record periods when the Uniab was effectively dammed by the dune barrier with stilled flood waters depositing suspension fallout (Blümel et al., 2000).

2.3. The Uniab Poort Profile

Fluvio-aeolian sediments of considerable thickness (>30 m) occur both in the breakthrough and the poort area. An extensive and well accessible profile was excavated during flooding in early April 2000 and was examined in close detail. The outcrop, termed the Uniab Poort Profile, consisted of a 290-m-long 1–5-m-high section of fluvial, lacustrine and aeolian sediments (Figs. 4 and 5). However, the physical nature of unconsolidated aeolian sand leads to a very low preservation potential of outcrop. As soon as the freshly cut bank surface dried most of the aeolian sand was rapidly hidden in bank collapses, which affected particularly the 105–145-m interval of the measured section, a strip made-up entirely of aeolian sands.

Another important factor concerns the contrasting resistance of fluvial sands, aeolian sands and lacustrine muds to wind erosion, including abrasion. Compared to the original depositional environment, there is undoubtedly an over-representation of muddy sediments in the profile due to the enhanced relative erosional resistance even of cohesively consolidated muds relative to wind erosion of aeolian and fluvial sands. Strict care and allowance should therefore be used in utilizing sand/shale ratio in the palaeoenvironmental interpretation of equivalent ancient fluvio-aeolian deposits. Fluvial sediments contain more fines compared to aeolian sediments, causing a pronounced bias towards the former in the fossil record.

3. The Uniab depositional setting

3.1. General lithofacies

Analysis of the Uniab outcrop involved measurement of bed geometries, bed thicknesses, grain size data and facies associations (Figs. 4 and 5). Idealized sections for the various flow types identified are drawn in Fig. 6. Grain size analyses of 10 samples from selected facies types were carried out using dry sieving, the results of which are shown in Fig. 7, together with calculated grain size parameters such as mean, median, sorting and skewness. Whole rock geochemical data from 61 samples were obtained by XRF. In addition, the clay mineralogy of the fines was examined using XRD analysis.

3.1.1. Facies ED: aeolian dune deposits

The well-sorted nature and grain roundness of this medium quartz sand facies, together with the absence of mica, lithics and grains < 2 mm, are typical of aeolian sediments. Sets 0.2 to 2.4 m thick are characterized by steep tabular north–northeastward inclined cross beds. The restricted variability in dip direction suggests straight to slightly sinuous-crested dune forms. The aeolian stratification is interpreted to result from combined grainfall and grainflow lamination (Hunter, 1977; Clemmensen and Abrahamsen, 1983), widespread in transverse dunes with steep lee-sides (Kocurek, 1991). The dip-directions within the dunes suggests a prevailing south–southwesterly

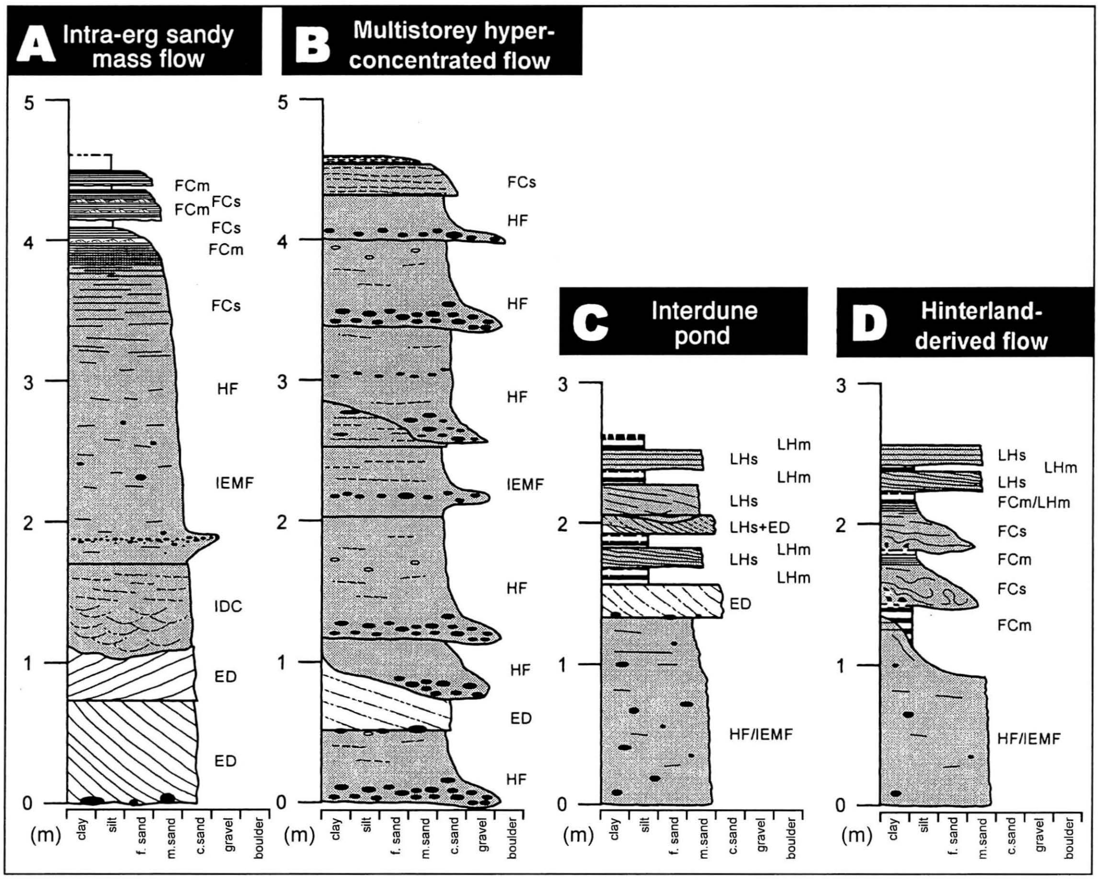

Fig. 6. Typical (idealized) facies associations in the Uniab Poort section. Notice the great variety of fluvio-aeolian interaction.

palaeowind direction (Fig. 8), similar to that of the present-day northern Namib Desert (Lancaster, 1982; Ward, 1987). Sharp based planar clast rich horizons below the base of facies ED units are as thin (< 1 cm) as a single clast diameter and are interpreted as deflation surfaces, in which original fine matrix material has been removed by aeolian winnowing.

3.1.2. Facies IDC: inter-dune channel deposits

This facies is characterized by trough cross-bedded and plane-laminated, well sorted medium-quartz sand with frequent mud clasts associated with the erosional based flat lens-shaped units. Bed thickness vary from 0.2 to 1.0 m with an obvious thickening related to topographic lows of the underlying aeolian dune facies ED. Facies IDC thus shows a close textural and compositional similarity with facies ED but records sedimentary structures typical of fluvial deposition. Such a similarity between ED and the channeled facies IDC can be explained by fluvial reworking of aeolian sand in wide shallow-braided river channels and the mix of trough cross-bedding and plane lamination implies deposition under both upper and lower flow regime conditions.

3.1.3. Facies IEMF: intra-erg mass flow deposits

Facies IEMF comprises moderate to well-sorted medium sand beds 0.2 to 3.0 m thick with a relatively large lateral extent of 40 to 60 m (Figs. 4 and 5). Two types of clast occur, mud clasts (< 18 cm), and rounded lithic, dominantly basaltic pebbles (5 to 16 cm). Particularly soft clasts are horizontally aligned and are located 5–10 cm above the unit bases as floating clasts, occasionally defining reverse grading.

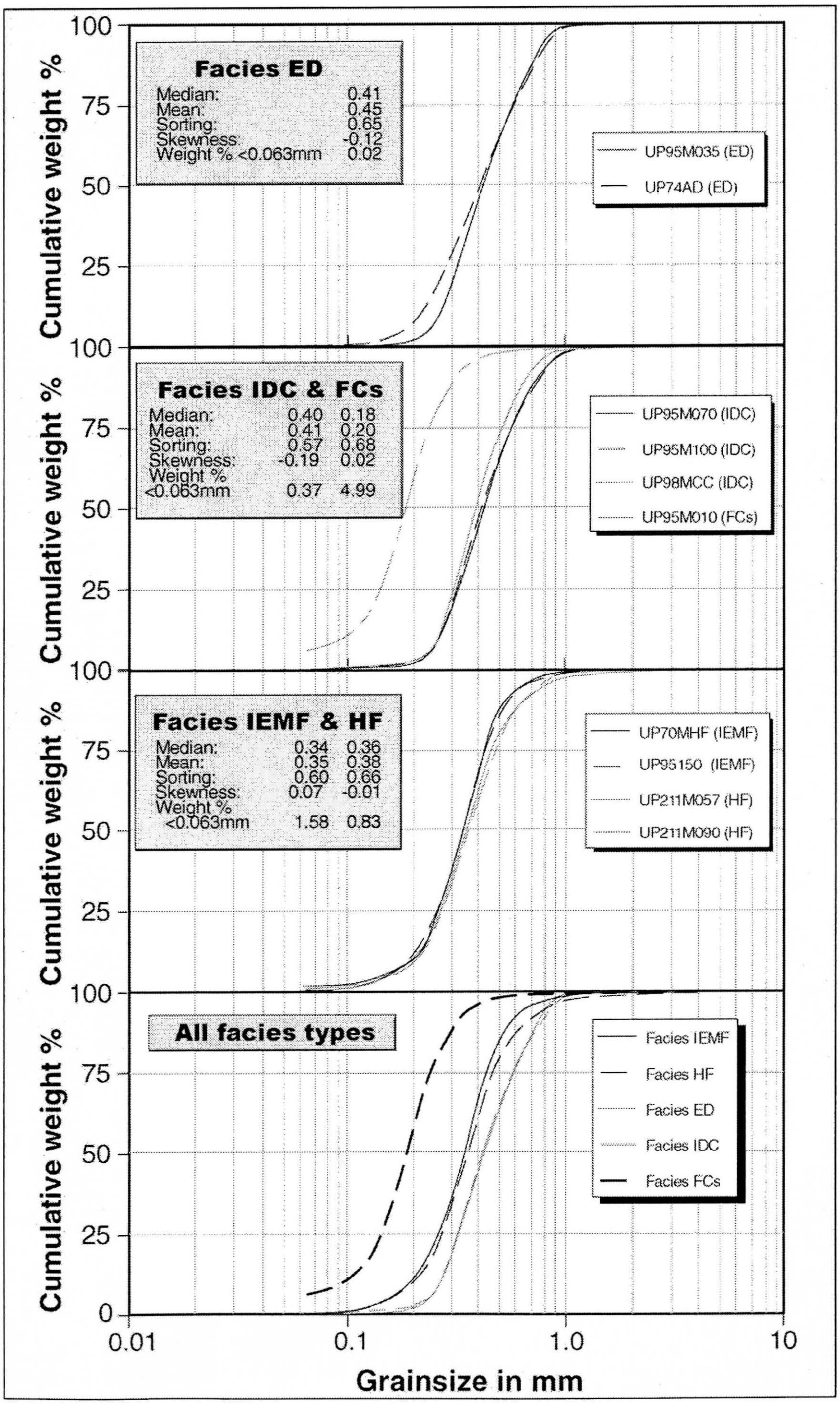

Fig. 7. Grain size data of 10 selected samples from the Uniab Poort profile. Sample names and facies types are marked in every case. It is noteworthy that facies IEMF and HF plots between facies FCs and ED, but closer to ED. This indicates that facies IEMF and HF could be formed as a mixture of FCs and ED, with a dominance of facies ED.

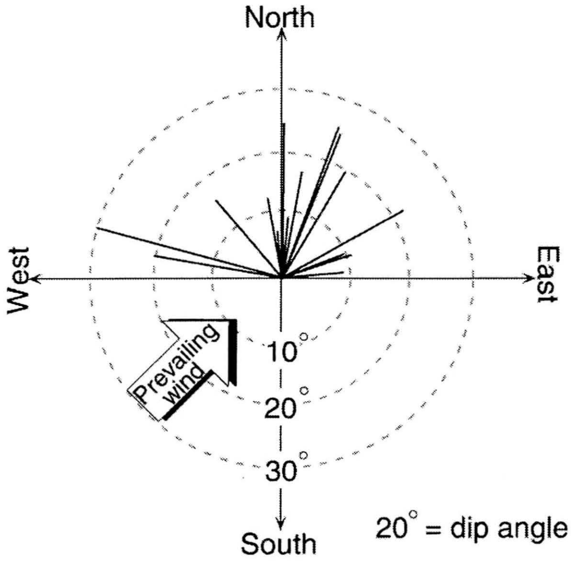

Fig. 8. Wind direction rose based on the aeolian foresets in the examined outcrop. The prevailing wind direction is from southwest. Circles indicate dip angle for each examined foreset.

Bed thickness is controlled by the underlying dune topographies with facies IEMF passively infilling and draping topographic lows. Upper contacts are gradual into facies HF (Fig. 6A).

The absence of sedimentary structures, poor sorting and the occurrence of floating clasts suggest that facies IEMF is a low-viscosity mass flow deposit (cf. Smith, 1986). The lack of erosional capacity (Jiongxin, 1999), and the lowermost part showing reverse grading also support this interpretation (Smith, 1986). The reverse grading is caused by dispersive stresses (e.g. Ballance, 1984; Smith, 1986), which are only efficient within the basal part of the mass flow (Lowe, 1982; Smith, 1986). Facies IEMF classifies variously: (1) as a cohesive sandy mass flow deposit, using the criteria of Nemec and Steel (1984), Smith (1986), and Todd (1989) ; (2) as a hyperconcentrated flow deposit, using criteria from Beverage and Culbertson (1964); or (3) as a mixture between these two types, using criteria from Jiongxin (1999) and Sohn et al. (1999). The term intra-erg mass flow is applied here to avoid a confusion of terms between this facies and clay-rich or debris-rich flow types described in the literature. Previously, it has been used by authors dealing with a similar reworked dune sand facies (e.g. Loope et al., 1998, 1999; Benan and Kocurek, 2000).

3.1.4. Facies HF: hyperconcentrated flow deposits

This facies comprises 0.2–2 m thick beds of 10–30 m lateral extent, thus expressing low width–depth ratios of about 10. Sediments are moderately to well sorted, ranging from fine sand to cobbles, although fine to medium sand dominates. Normal grain size grading is well developed, with a basal conglomerate in almost every unit. Basal contacts of facies HF beds are variable and include gradual transitions from facies IEMF into HF or sharp erosional-based contacts (Fig. 6A and B). Clasts in the basal conglomerate are horizontally oriented and frequently show imbrication. The facies type is characterized by sub-horizontal to undulating lamination sometimes denoted by pebble layers. Clasts are of both intra- and extraformational origin, the first made of mud clasts, the latter almost entirely of rounded basaltic clasts. Some floating clasts were observed. The clasts measured in the Uniab Poort section display a wide range in diameters of 5–200 mm.

The presence of the erosional lower contact and a basal conglomerate suggest that facies HF is deposited by a bedload-dominated turbulent flow. The absence of cross bedding and other sedimentary structures suggests hyperconcentrated flows, where the high sediment-load (non-turbulent flow) disables development of sedimentary structures, as described by Smith (1986). The normal grading indicates that flow velocities decreased during deposition and the upper part might be deposited under normal streamflow conditions.

A notable zone of up to 5 × 4 m large boulders has been observed 0.5 km downstream of the Uniab Poort. These blocks occur isolated or in clustered sets and consist of locally derived cemented Uniab terrace material (Fig. 9). They either sit within a channel or on channel banks at elevations 2–3 m above the adjacent channel floor, favourably close to drainage divides. It is not known when these large boulders were moved. However, Scheepers and Rust (1999) noticed an association of large boulders with plant flotsam, including woody material, sticks and small trunks at the same elevation above the active channel floor and concluded a maximum age of a few decades at least for the deposition of the plant remains. We

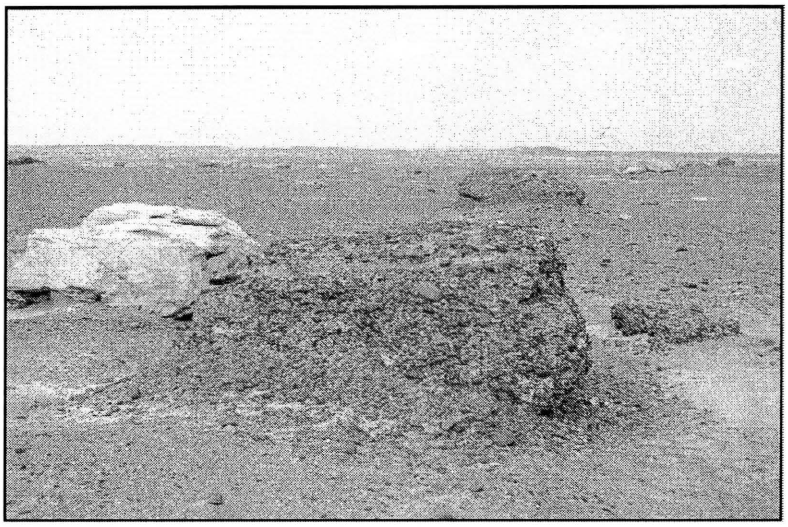

Fig. 9. Large blocks of lithified (A) sand dune and (B) Uniab terrace deposits, most probably transported by hyperconcentrated flows. Diameter of large block in front is 3.2 m.

suggest that the most convenient way to transport boulders of the described size would be through high-magnitude hyperconcentrated streamflows, in which high sediment concentration and enhanced yield strength buoyancy of the sediment–water mixture provide sufficient support to transport boulders (cf. Pierson and Costa, 1987).

3.1.5. Facies FCs: fluvial channel deposits (sand)

This comprises 0.3–1.4 m beds of moderately sorted fine sand with rare clasts of both intra- and extra-formational origin. The most common structures are horizontal lamination or low-angle cross-bedding, but also planar cross-bedding, slumping and massive beds are developed. The laminated sediments are found in 2–15 cm sets, each displaying upward-fining, which is typically accentuated by a delicate colour variation. Where facies FCs is found as a gradational transition from facies IEMF or HF (cf. Fig. 6A and B), it suggests a record of waning flow following a flood event (cf. Pierson and Costa, 1987). Facies FCs may represent the onset of more regular stream flow conditions with development of smaller migrating barforms after the chaotic hyperconcentrated flows and mass flows had passed downchannel. Where facies FCs is found in scours, FCs represents normal fluvial conditions through the erg, probably in a well-established channel.

3.1.6. Facies FCm: fluvial channel deposits (mud)

Thin to medium (5–40 cm thick) beds of dark brown mud, generally well sorted; only rarely is poor sorting seen. Where deposited as a thick mud layer, the facies commonly forms flame structures into the overlying sediments, due to syn-sedimentary load deformation. Small wood fragments and particles of organic matter are found within this facies type. The fine-grained fraction is deposited from suspension in abandoned thalwegs or scours between larger bedforms and marginally drape them (Fig. 4, 30–50 m).

3.1.7. Facies association LH: lacustrine heterolithics

An association that comprises sandy (LHs) and muddy (LHm) subfacies. The latter facies is represented by isolated thin (1–15 cm) or stacked silt and clay beds, frequently desiccation cracked, with flat lenticular geometries and at least 10–30 m lateral extent. These drape over underlying topographies to some extent but pinch out against larger dune forms to exhibit concave-up cross-sections (Fig. 4). Facies LHm is interpreted to represent suspension-fallout deposited in variably sized interdune ponds (cf. Ahlbrandt and Fryberger, 1981; Langford and Chan, 1989). The stacking of facies LHm suggests that the interdune pond development happened frequently, and that a complete aeolian cover of the pond was inhibited.

It is noteworthy in this context that widespread mud deposits of an equivalent facies are exposed at the "Mudlayer Valley" locality (Figs. 2C and 3) at levels of more than 8 m above the present Uniab river bed. Deposition of mud at this elevation would certainly imply a base level rise compared to the present-day. Equivalent lithologies but with no interbedded dune deposits associated also occur east of the erg as widespread erosional remnants up to 0.7 m thick. The occurrence of these beds is restricted to the east and northeast of the area where the Uniab enters the erg (Fig. 2D). Such an association has recently been described by Stanistreet and Stollhofen (2002) from the Gui-Uin flood basin (Fig. 2B) that formed by damming of the Hoanib River against the dune barrier further north.

Facies (LHs) is only rarely seen in the measured sections but has been observed in association with recent interdune ponds along the Uniab river course (Fig. 6C). It is made-up of erosional based, moderately sorted, cross-bedded medium sand that forms beds 10–40 cm thick with a linear 5–10 m extent. Similar facies were related by Stanistreet and Stollhofen (2002) to combined inflow delta and outflow channels feeding and draining modern interdune lakes along the Hoanib river course.

3.2. Properties of Uniab hyperconcentrated flow deposits

Sieving analyses and whole rock geochemical analyses (XRD and XRF) were carried out to gain information on the grain size distribution, the clay mineralogy and potential source areas of the hyperconcentrated flow deposits. Results of the grain size analysis are presented in Fig. 7.

3.2.1. Grain size

In general, grain size analyses (Fig. 7) confirm the field observation that the hyperconcentrated flow deposits consist of moderate to well sorted medium sand. Similar grain size parameters of facies ED and HF also confirm the interpretation of hyperconcentrated flow deposits to originate from reworking of aeolian sand dunes. Important is the presence of a < 2 wt.% mud fraction (< 0.063 mm) in the examined sediments. The total amount of clay has been estimated to total 0.8 wt.% using XRD and 1 vol.% by optical microscopy.

Clay content is one of the most important factors in controlling initiation and lubrication of hyperconcentrated flows and mass flows. The amount of clay proposed as adequate to form the different flow types varies considerably, depending upon the definition of the different flow types (Hampton, 1972, 1975; Rodine and Johnson, 1976; Coussot and Meunier, 1996; Major, 2000). Some authors (e.g. Beverage and Culbertson, 1964) have suggested that a minimum of 10–15% clay is needed to form hyperconcentrated flows and mass flows. However, Hampton (1975) reported that as little as 1.5–4 wt.% smectite mixed into water was sufficient to support fine sand.

The measured amount of mud (< 0.063 mm) in our sieving analyses does not necessarily record the original amount of fines during the flood flow, as parts of the clay fraction might be removed by syn- to post-depositional fluid flow (cf. Jones and Blakey, 1997; Major, 2000). Evidence for two processes (A) downward-directed mud infiltration and (B) upward-directed fluid flow (Fig. 10) are present in the Uniab sections: The majority of the examined Uniab flood flow sediments (facies IEMF and HF) are characterized by a thin (0.5–1 mm) mud layer at the base of the unit, which drapes the undulating basal contacts (Fig. 4). Examination of contact relationships reveals that these mud layers result from infiltration of sediment-laden flood waters into the underlying porous sediment, leaving behind a thin mud cake at the base of the flows (Figs. 4, small inset and 10). In addition, upward-directed water-escape structures, some with flame-like geometries, occur. We conclude, therefore, that the original amount of fines may have been higher during the actual flow than the observed values in the remaining deposits, but most probably did not exceed 2–4%. This amount would coincide with the data from Hampton (1975) which proposes sufficient matrix strength and buoyancy to support finest sand by only 1.5–4% mud.

3.2.2. Clay mineralogy

Both the amount of clay and the clay mineralogy are of great importance for the shear strength of high sediment loaded flows (Trask, 1959; Hampton, 1972, 1975; Rodine and Johnson, 1976). XRD analyses carried out on the mud fraction of facies IEMF revealed a clay composition of 85% smectite, 10% kaolinite and 5% illite. XRF analyses of 10 mud samples from the

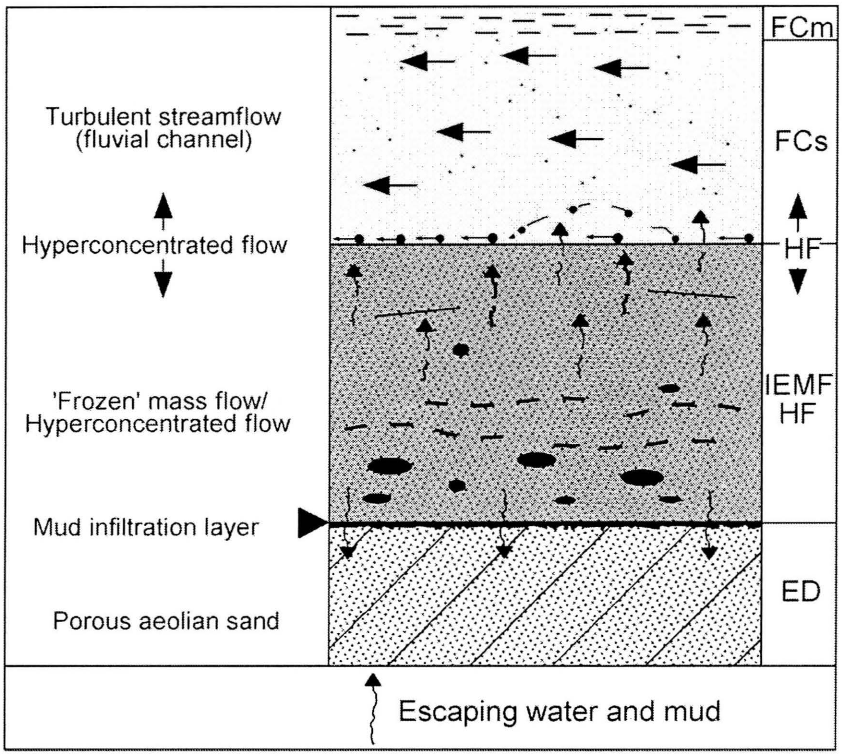

Fig. 10. Schematic drawing of fluid migration in hyperconcentrated flows and mass flows. Although both upward and downward movements of fluids are recognized, none of them are believed to play a major role in redistribution of fine grained material.

Uniab Poort outcrop indicate an enrichment of CaO, MgO and Na_2O and a depletion of K_2O compared to average mud (Fig. 11), which confirms the dominance of smectite. In addition, the Uniab muds show an obvious geochemical similarity to the Etendeka basalts exposed in the Uniab source area (Fig. 11), suggesting that the smectite formed as weathering product of the basalts (Deer et al., 1992, pp. 369–376; Tomita et al., 1993). Such a dominance of smectite is well known from weathering products of various other basaltic terrains including Hawaii and the Columbia River plateau basalts (e.g. Johnsson et al., 1993).

According to Trask (1959), the strength of a flow increases significantly if smectite, rather than illite or kaolinite dominates. A flow with 10% illite or kaolinite will have the same strength as a flow with as little as 2% smectite (Trask, 1959; Rodine and Johnson, 1976), explaining why the Uniab hyperconcentrated flow and mass flow deposits could form with only 2–4% fine grained fraction involved.

3.2.3. *Whole rock geochemical composition*

Whole rock geochemical analyses were carried out in an attempt to discriminate between the different facies types. Sediments deposited in desert environments experience considerable reworking that hampers discrimination of different facies using geochemistry (North and Boering, 1999; Svendsen and Hartley, 2001). However, the setting in the Uniab mouth area, which shows strong provenance control, allows successful geochemical facies discrimination. The basaltic Etendeka catchment provides abundant CaO (plagioclase and clinopyroxene), whereas the aeolian source area south of the Uniab river course contains no dominant Ca-bearing minerals. Weathering in the Etendeka catchment area produces smectite, therefore the fine-grained fraction is enriched in CaO. It is necessary to normalize the CaO-data with Al_2O_3, to remove the effect of clay. A plot of SiO_2 vs. CaO/Al_2O_3 is then used to discriminate between the different facies (Fig. 12). Obviously, the individual

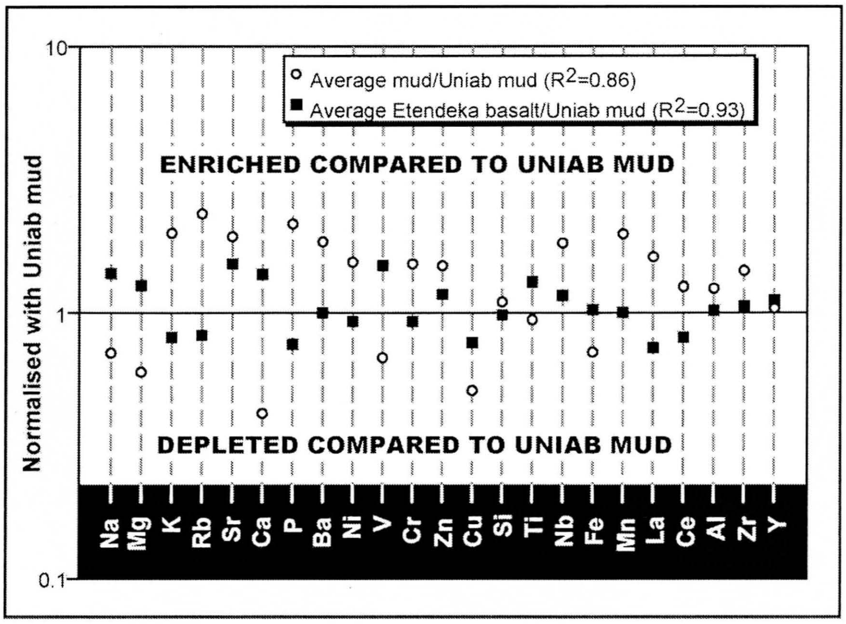

Fig. 11. Chemical composition of the Uniab mud, compared to average mud (open circles) and Etendeka basalts (solid squares). The Uniab mud is enriched in Na, Mg and Ca compared to average mud, suggesting that the Uniab mud is rich in smectite. R^2 values show that Uniab mud mimics the source area better than it mimics average mud, suggesting that all mud in the Uniab River is derived from weathering of the Etendeka basalts. Average mud data from Taylor and McLennan (1985), Mason and Moore (1982) and Cosgrove (1973). Average Etendeka basalt composition from Marsh et al. (2000).

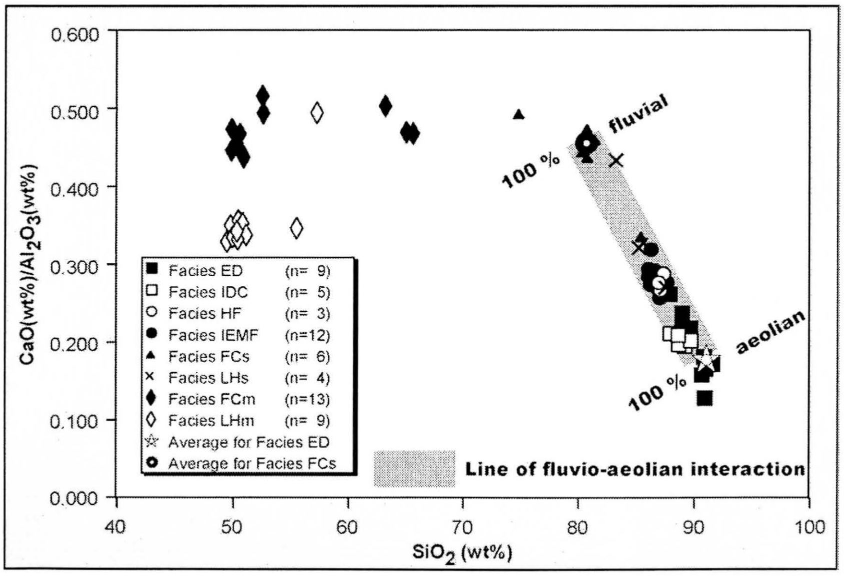

Fig. 12. Facies discrimination using whole rock geochemistry. The fluvial source area is rich in CaO, and the eolian source is rich in SiO_2. By plotting these two end members, a clear facies discrimination is seen. However, before using CaO, it is necessary to normalize with Al_2O_3, to avoid non-facies related affects from fine material. By adding in a line of fluvio-eolian interaction between the two end members, ED and FCs, it is possible to estimate the degree of reworking.

facies cluster and enable basic facies discrimination. Furthermore, the plot can be used to estimate the degree of fluvio-aeolian interaction, by adding a line from the average ED to the average FCs. This line represents an end member aeolian sediment on the lower right and an end member fluvial sediment on the upper left. The three facies types IDC, HF and IEMF all plot along this line, allowing an estimate on the amount of aeolian reworking. Facies IDC (inter-dune channel with reworked aeolian sand) comprises ca. 90% aeolian sand, whereas the HF and IEMF plot in the same area with approximately 50–70% aeolian sand. The estimated degree of reworking based on geochemical constraints is supported by the sieving data (Fig. 7), where facies IEMF and HF plot intermediate between facies ED and FCs. Although it is not possible to make an exact number from this plot, it is clear that HF and IEMF plot closer to ED than to FCs, suggesting 50–70% reworking.

4. Mass and hyperconcentrated flow generation in the Uniab fluvio-aeolian setting

Several authors have described fluvial interaction in ancient erg settings (Porter, 1987; Clemmensen et al., 1989; Cowan, 1993; Meadows and Beach, 1993; Frederiksen et al., 1998; Loope et al., 1999), particularly in the areas of the erg margin and fore erg (Porter, 1986), but only rarely were intra-erg hyperconcentrated flows or mass flows included in such studies. Popular scenarios that include reworking of aeolian sand have been documented previously by:

- Eschner and Kocurek (1986) and Benan and Kocurek (2000), who described the 'geologically instantaneous' drowning of an erg and the resulting mass flows (Jurassic Entrada Sandstone, USA), as a marine transgression rose above the dune field;
- Loope et al. (1998, 1999), who described the formation of 'lethal sandslides' produced by heavy rainfall in an erg resulting in 'alluvial fans' at the foot of the dune (Cretaceous Djadokhta Sandstone, Mongolia);
- Jones and Blakey (1997), who reported the occurrence of fluvial sandstones deposited in the erg margin as a result of local avulsion, possibly caused by aeolian damming (Jurassic Page Sandstone, USA).

In the first two cases, the resulting sediment has been described as a structureless sediment-gravity flow passively infilling the dune palaeotopography, with the reworked aeolian sand found adjacent to its dune source. The latter study describes sandy mass flows caused by fluvial reworking of aeolian sand. In this case, aeolian damming at the erg-margin caused the intra-erg mass flows. The source area for the intra-erg mass flow of the Page Sandstone exposes rhyolitic ignimbrites, volcanic material that weathers to produce 5–15% smectite (Jones and Blakey, 1997). The Uniab area displays many similarities with the Page Sandstone and it is believed that the two reflect a comparable depositional environment. The Uniab area thus provides the modern analogue desired by Jones and Blakey (1997).

To discriminate between allochthonous and autochthonous mass flow types, the terms 'attached' and 'detached' intra-erg mass flows are proposed here. Attached intra-erg mass flow is a term ascribed to the collapsing dunes described by Benan and Kocurek (2000) and by Loope et al. (1998, 1999) creating mass flow sediments which are deposited as fans attached to the aeolian source. In contrast, the term 'detached' intra-erg mass flow refers to fluvial reworking of aeolianites and their transport and deposition distal to the original aeolian source. The latter type is described in our study and by Jones and Blakey (1997). Where exposure is limited or information restricted to cores, it might be difficult to distinguish between the two types. However, the presence of lithic clasts and of a geochemically contrasting 'hinterland' signature would still record the source area signal and are therefore regarded as evidence for detached intra-erg mass flows.

A model to explain the formation of flood sediments exposed in the Uniab Poort Profile must be consistent with several observations:

- The occurrence of stacked thin but widespread mud deposits east of the erg and north of the present-day Uniab river course.
- The occurrence of stacked flood pond sediments interbedded with aeolianites within the dune field, 8 m above the present-day river bed.

- The repeated generation of compositionally similar flood flow sediments in adjacent interdune areas.
- The modelled reworking of 50–90% aeolian sand.
- The occurrence of erratic 5 × 4 m large blocks between the erg exit and the Atlantic Coast line.

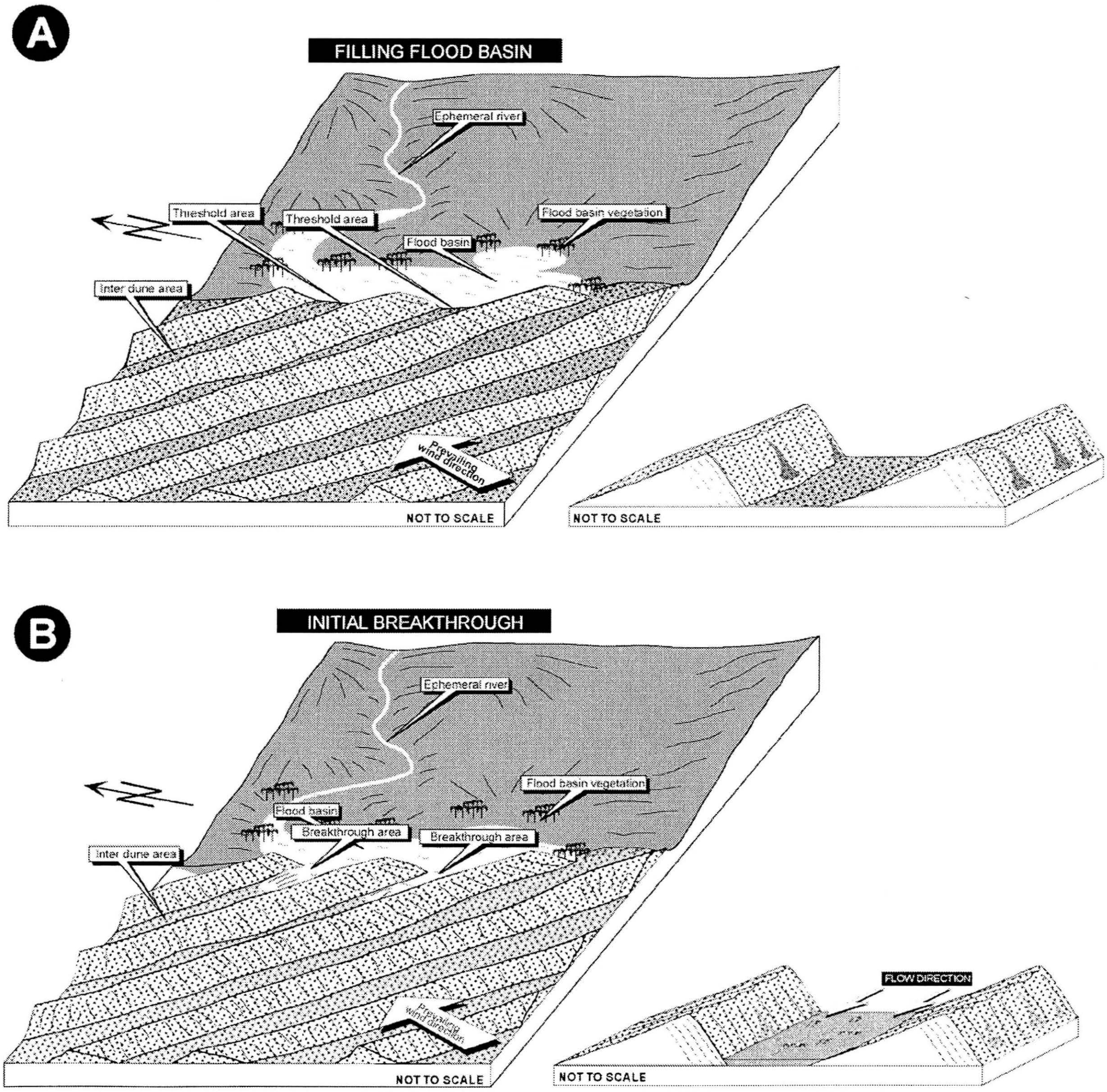

Fig. 13. Proposed model to explain the observed deposits in the Uniab Poort profile. (A) First stage comprises filling of the flood basin E of the erg. (B) Second stage is an initial breakthrough causing flooding of interdune areas. (C) Dunes in the flooded zone become soaked by floodwaters and once these start to filter through the dunes, these become unstable, collapse and give way to major runoff, frequently generating hyperconcentrated flows. (D) When hyperconcentrated flows have eroded heavily in the dunes, almost vertical cliffs of aeolian sand are left. This causes further dune collapse and the additional supply of large amounts of sediment. Consequently, the flow transforms from a turbulent hyperconcentrated flow into a laminar mass flow. This mass flow will lack erosional capacity, and will drape the underlying dune morphologies.

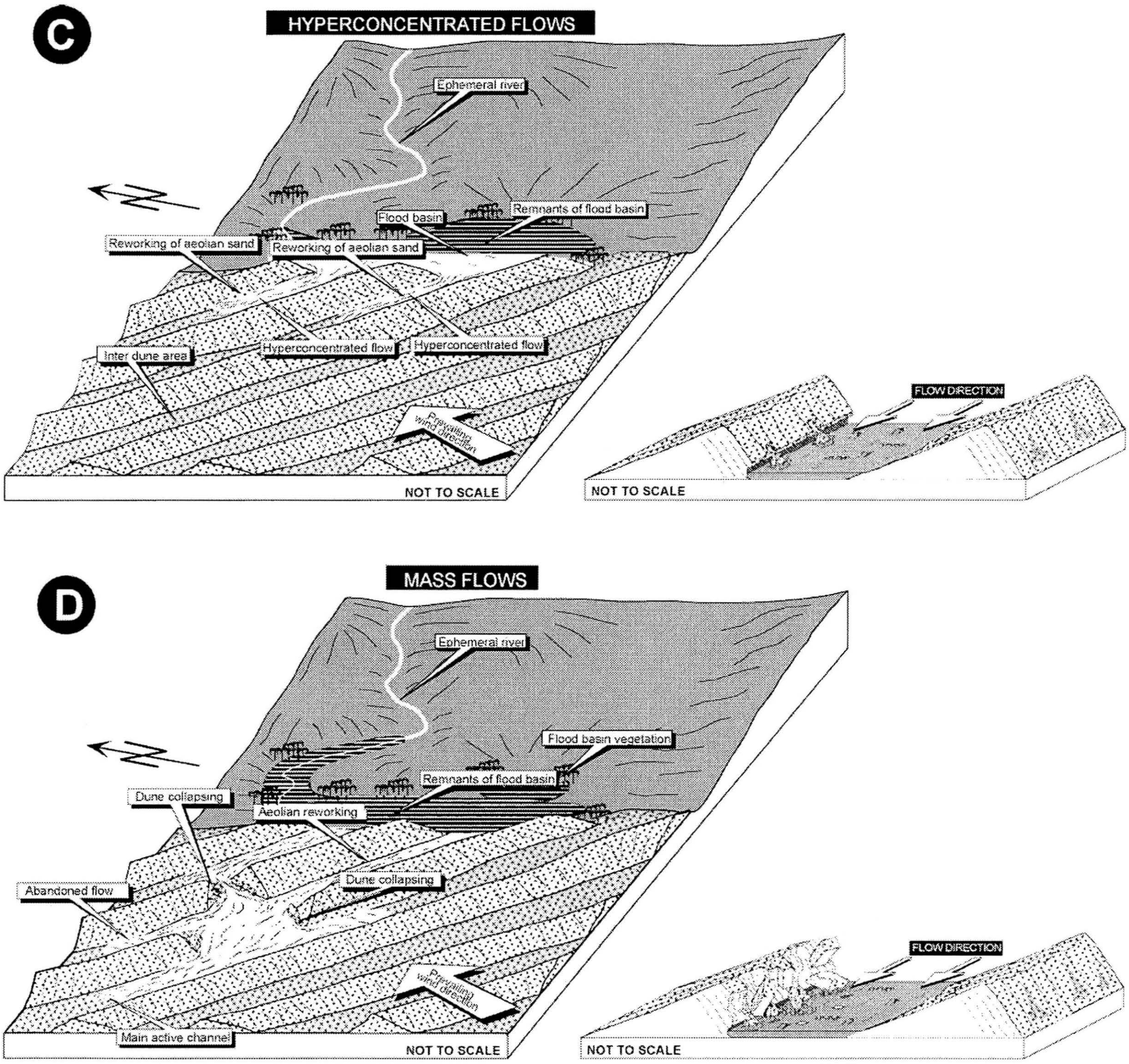

Fig. 13 (*continued*).

The simplest way to explain the observed deposits uses a dune damming model. Even if the present Uniab River maintains a well-developed channelway through the erg this was not the case throughout its history. Only in early April 1995 did the Uniab River break through the dunes which had blocked its path to the sea for 13 years since 1982 (Jacobson et al., 1995). Since then, minor floods in March 1997 and in April 2000 flushed the river course and prevented healing of the dune belt. OSL and TL-data of Namib Desert dune sands indicate enhanced aeolian activity and dune growth during the Last Glacial Maximum at about 18–22 ka (Blümel et al., 2000). Certainly this would have favoured dune damming, particularly because lowering of the average temperature was probably associated with a 30–40% decrease in average annual precipitation (Blümel et al., 2000).

The process of river dune damming was first described by Dobrovolny and Townsend (1947), and has later been reported by several authors from various locations worldwide (e.g. Langford, 1989; Teller et al., 1990; Loope et al., 1995; Jones and Blakey, 1997; Stollhofen et al., 1999; Muhs et al., 2000). The majority of previous studies dealt with the static damming and formation of lakes and flood basins, with only Jones and Blakey (1997) describing the fluvial consequence of these intra-erg floods. They consider local avulsion of erg-parallel rivers to be caused by aeolian damming, leading streamflow into the erg. Obvious dune damming is also seen to affect the Hunkab and Hoanib rivers further north in the present-day Skeleton Coast erg (Stollhofen and Stanistreet, 1997; Stanistreet and Stollhofen, 2002; Krapf et al., in press).

The model proposed here divides into five stages, illustrated by Figs. 13 and 14. Each figure shows an overall view of the proposed flooding and a detailed view of the kind of fluvio-aeolian interaction.

4.1. Filling flood basin reservoir

Initially, flood flows generated by exceptional rainfalls in the Uniab catchment and containing mud and sand derived from weathered Etendeka volcanics dam up against the eastern rim of the erg. A flood basin forms (Fig. 13A) with the minimum dune elevation dictating the heights up to which the dam lake can rise. Infiltration of flood-derived clay and draping by suspension-fallout of fines affects the threshold dune and may initially reduce or completely prevent seepage through the unconsolidated dune sand. Erosional remnants of stacked, laminated floodbasin muds, termed "river end deposits" occur over an area of at least 4 km N–S diameter (Blümel et al., 2000) E of the erg and preserve evidence for the repetitive existence of widespread dam lakes. The time required to fill the dam lake area is unclear, however, tens of days to few weeks

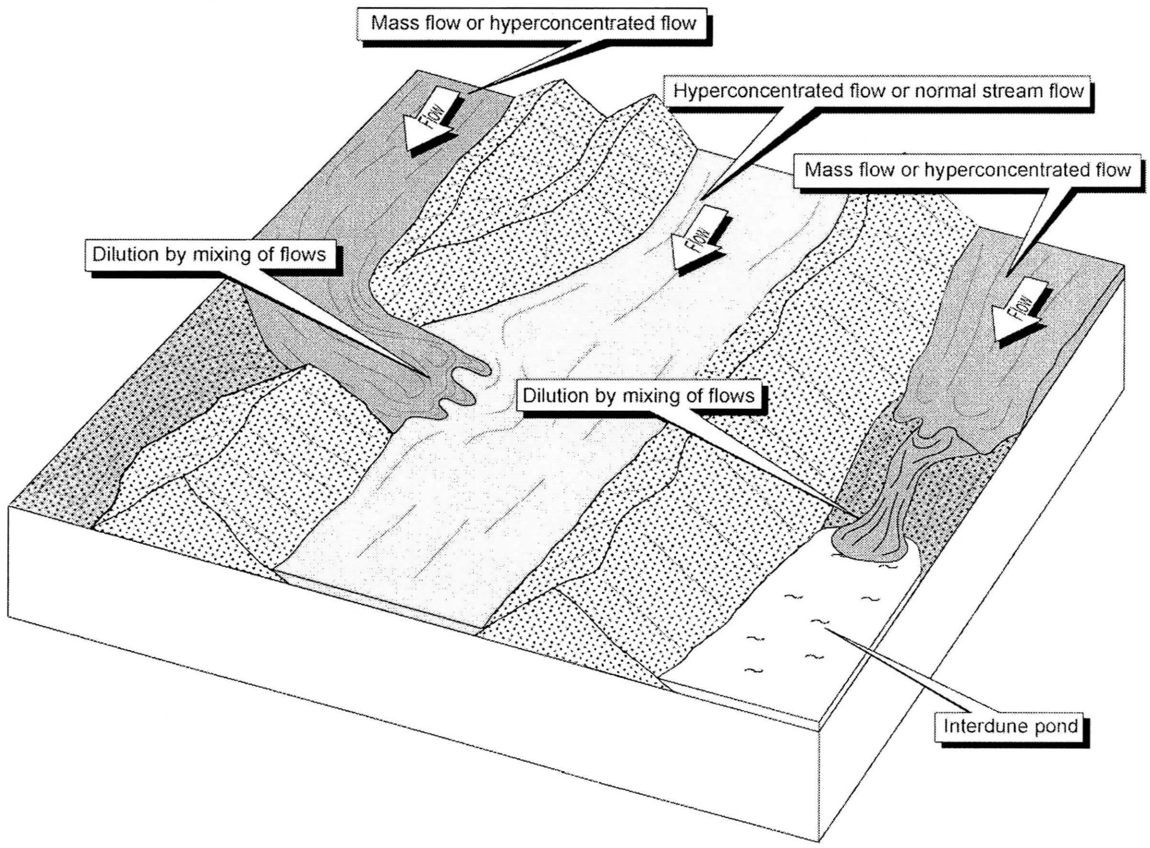

Fig. 14. Processes causing dilution of mass and hyperconcentrated flows in dune settings.

seems realistic when compared to the >10 days time which is required to fill the Gui-Uin flood basin associated with the present-day Hoanib river (Stollhofen et al., 1999). The Uniab flood basin was probably heavily vegetated, as seen presently in the Gui-Uin Basin in the Hoanib area. At this time, no fluvial activity occurs in the erg (Fig. 13A).

4.2. Initial breakthrough

Although there are several similarities between Hoanib and Uniab rivers, their type of dune damming is rather different: The northern Skeleton Coast erg reveals a more or less uniform erg topography with a continuously high elevation (>40m) of composite transverse dunes. As a consequence, rivers such as the Hoanib in the north are effectively dammed at the eastern erg margin, causing an extensive flood reservoir basin there. Floodwaters build up behind the dune barrier until the water-level within the flood basin is high enough to overtop a erg lowpoint. Once the threshold dune barrier has been overtopped, interdune trends guide the river through the entire dune field. In contrast, the southern part of the ergshows a considerable asymmetry, with low barchans in the east but a high dune wall in the west. Consequently, rivers such as the Uniab develop only minor flood basins outside (east) of the dune belt but cause widespread flooding within the erg as the most pronounced barrier is provided by the dunewall at its western border. Unsuccessful attempts by the river to cut through the erg are recorded by widespread stacked interdune mudlayers deposited at elevations up to 8 m above the present-day Uniab river bed.

The initial breakthrough of a flooding Uniab River may be simply performed by overtopping, when the water level in the flood basin reaches the heights of the threshold dune, flows over its crest, and quickly erodes down into the dune sand (Fig. 13B). The mud-rich floodwaters then flood Uniab channel remains and interdune depressions within the erg but are still dammed by the main dunewall at the western side of the erg.

4.3. Final breakthrough and the generation of hyperconcentrated flows

This is induced by several contemporaneously active processes: (I) Piping through the dune barrier in areas where flood water muds provide a less well-developed seal for the dune sands, making them permeable. (II) Once the flood waters started gradually permeating the aeolian sands, the large, elevated dune forms become too weak to hold up their own weight and are susceptible to gravitational collapse. (III) If flood waters push through a permeable layer of sand beneath the threshold dune and break through the ground on the other side (underseepage), this would significantly weaken the ground on which the dune sits and destabilize it. Cases I–III would be particularly favoured by enhanced hydrostatic pressure developing with a rising flood water level.

Consequently, dunes in the flooded zone become soaked by floodwaters and once these start to filter through the dune barrier this becomes unstable, collapses and gives way to major runoff. Once breakthrough is managed, additional water-saturated dunes along the newly formed river course collapse, a process that is enhanced by fluvial undercutting of the aeolian dunes. Collapse of water-saturated dunes along the river course abruptly increases the sediment load of the flow. At this stage the "normal" river flow transforms into a hyperconcentrated stream flow (Facies HF), a turbulent flow with high erosional capacity. Undercutting and collapse of the dunes thus create a latent sediment source, and lead to almost vertical sand cliffs, due to high intergranular water content that creates adhesive capacity (Jacobson et al., 1995). The hyperconcentrated flows follow the trend of interdune areas (Fig. 13C) and respond to the new, lower base level datum of the South Atlantic Ocean. Hence, they are forced through the erg (gradient approx. 1.6°), causing rapid erosion and downcutting there. This also explains the formation of fluvial and lacustrine sediments 8 m above the present Uniab level in Mudlayer Valley (Fig. 2). If no additional sediment is supplied to the flow, it will deposit the coarsest material as velocity reduces and the flow changes from a hyperconcentrated flow into normal streamflow (Facies FCs). No significant infiltration is believed to occur, and a transition into laminar mass flow due to loss of water is not anticipated.

4.4. Mass flows

If the turbulent hyperconcentrated flow continues through the erg (Fig. 13D), undercutting of the dunes reaches a critical value and the steep aeolian sand collapses into the flow, as described by Andrews (1981) and Langford (1989). In some cases, these instantaneous supplies of large volumes of aeolian sand will further increase the sediment concentration, and the flow will change from a turbulent hyperconcentrated stream flow to a laminar mass flow (cf. Fig. 1). As the flow changes nature from turbulent to laminar flow, it loses the erosional capacity and continues through the erg as a passive fluid draping the topography provided by aeolian bedforms (Facies ED).

4.5. Dilution of flows

As the mass flow (Facies IEMF) passes through the interdune area, it deposits part of the sediment load, leading to a decrease in sediment concentration, thus transforming the flow into a hyperconcentrated flow (Facies HF) or a "normal" stream flow (Facies FCs). As a mass flow encounters an interdune area already filled by a pond lake or a normal stream flow, it may become diluted, thus changing from a mass flow into a hyperconcentrated flow (Facies HF) (Fig. 14).

5. Conclusions

Hyperconcentrated and mass flow deposits from the Uniab area of the Skeleton Coast, Namibia, are interpreted to result from aeolian damming of ephemeral rivers, causing catastrophic flooding of the erg when the threshold dune dam is overtopped. Dunes in the flooded zone become soaked by floodwaters and once these start to filter through the remaining dune barrier this becomes unstable, collapses and gives way to major runoff. Resulting high sediment concentrations frequently generate hyperconcentrated streamflows. Unsuccessful attempts by the river to cut through the erg are recorded by widespread stacked mudlayers deposited within flooded interdune depressions of the erg.

Detailed grain size and geochemical analyses reveal important insights into the relationships between source areas and depositional processes. The basalt-dominated Uniab catchment weathers to produce dominantly smectite, allowing the flood flows to obtain certain strength, not possible to that extent if the clay minerals were illite or kaolinite. The difference in clay mineralogy explains why the dune damming processes in the nearby Hoanib area do not produce sandy intra-erg mass flows and hyperconcentrated stream flows observed in the Uniab area. The missing mass flows can be explained by the Hoanib catchment area composition, which consists dominantly of metapelitic and quartzitic rocks. Weathering of these bedrocks produces illite and kaolinite, rather than smectite (Eitel et al., 1999). Even if the overall clay content in the two rivers is comparable (ca. 2–4%), the Uniab area will produce mass flows as the majority of the clay is smectite, thus giving the flow the required strength. The flows in the Hoanib area, with the same clay content (2–4%), will have little if any smectite, and consequently cannot obtain the strength required to produce mass and hyperconcentrated flows.

An improved understanding of fluvio-aeolian interaction is also of substantial economic importance as resulting deposits provide suitable reservoirs for hydrocarbons (cf. North and Prosser, 1993). The Skeleton Coast erg appears to be a reasonable analogue for several ancient erg-margin settings, and the hyperconcentrated flood deposits of the Uniab area provide an innovative explanation for the formation of thick massive sandstone units with aeolian sand grain characteristics in these settings.

In addition, flood flows are a major hazard in many parts of the world, responsible for the losses of many lives. Consequently, the prediction and understanding of these floods are of crucial importance. For many people, these floods may occur randomly and without any reliable prediction (cf. Zawada, 1994, 1997). Many reports of devastating flood flows are reported from volcanic areas (e.g. Hodgson and Manville, 1999; Manville et al., 1999). Although the unconsolidated material and the related active tectonics might be the most important parameters, this study has shown that smectite in the sediment might be of crucial importance for the initiation of hyperconcentrated flows and mass flow, capable of transporting large boulders and blocks.

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