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Hoanib River flood deposits of Namib Desert interdunes as analogues for thin permeability barrier mudstone layers in aeolianite reservoirs

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ABSTRACT

The ephemeral braided Hoanib River of NW Namibia flows for a few days a year, and only high discharges enable the river to pass through interdunal depressions within the northern Namib Desert dune field to the Atlantic. The dune field comprises mainly large transverse dunes resulting from predominant SSW winds. River flood deposits between aeolian dunes are analogous to mudstone layers conformably interbedded with ancient aeolianite dune foresets. Deep floods pond laterally to considerable depths (metres to >10 m) in adjacent interdunes, depositing mud layers (1–50 cm) to considerable heights on avalanche and stoss faces of bounding dunes. Fairly passive flooding only disturbs aeolian stratification minimally. Floodwater clay infiltrates and settles as an impermeable seal, with a flood pond on top, perched, above regional groundwater. Flood ponds evaporate slowly for long periods (>3 years). Early emergence desiccates higher parts of a mud layer. Subsequent floods can refill a predecessor pond, benefiting from the existing impervious seal. Potential preservation of such mud layers is lower on the stoss face, but high on the avalanche face after burial by subsequent dune reactivation and migration. The leeward (right) Hoanib bank, a dune stoss face, is river and wind eroded to exhume fossil interdune pond mud layers of an earlier Hoanib channel. The highly inclined layers are interbedded with dune avalanche foresets and represent the edges of two successive fossil ponds exposed in plan. Ancient flood pond mudstones occur in the Permian–Triassic hydrocarbon reservoir, the Sherwood Sandstone Group of the Cheshire Basin (Kinnerton Formation) and Irish Sea Basin and were previously used erroneously to argue against the aeolian origin of cross-bed sets. Hoanib studies show that primary river interaction with a dune field might preserve only localized erosional omission surfaces in ancient aeolianites, with little sandy barform preservation, prone to aeolian reworking. Around the main fluvial channel locus, however, flood pond mudstone layers should form a predictable halo, within which fluid permeability will decrease.

Keywords Aeolian dunes, aeolianite reservoir, flash flood, interdune, Namib desert, Namibia, permeability.

INTRODUCTION

High-discharge floods of the Hoanib River occasionally break through the Skeleton Coast dune field, which forms part of the extensive Namib Desert that parallels the western margin of the southern African subcontinent. This arid region is <140 km wide and over 2000 km long from south-western Angola to the northern Cape Province, South Africa. The northern Namib dune field, termed the Skeleton Coast dune field by Wilson (1973), Lancaster (1982) and Ward &

Corbett (1990), is 6–20 km wide and extends for about 200 km between ≈18°S and ≈20°S latitude, characterized by simple, and locally compound, transverse and barchanoid dune forms, 20–50 m high (Lancaster, 1982, 1983). The prevailing NW to WNW alignment of the dunes is transverse to the dominant, strong south-west to south-south-west onshore winds and the climate is hyperarid. In contrast, the area north of the Namibian/Angolan border at about 17° latitude classifies as an arid summer rainfall desert and that south of the Namibian/South African border at about 29°S as an arid winter rainfall desert (Ward, 1989). Regional climate is controlled by: (1) the intensity of the cool northward-flowing Benguela current offshore, causing dry south-westerly winds; (2) the subtropical South Atlantic anticyclone towards the south, centred offshore between Lüderitz and the Orange River mouth; and (3) monsoonal influences from the north and east, which are associated with disturbances of the intertropical convergence zone (Van Zinderen Bakker, 1984; Tyson, 1986; Jury, 1996; Ward & Swart, 1997; McCarthy *et al*., 2000).

The drainage pattern of the Skeleton Coast in NW Namibia is dominated by ephemeral streams that flow west-south-west towards the Atlantic Ocean from their catchment areas about 150–200 km inland. These rivers originate in north central to NE Namibia in highland areas with relatively high seasonal rainfall, ranging between about 300 and 600 mm per year, and pass through a steep climatic gradient towards the coast where annual rainfall declines to near zero. The majority of the rivers flow almost annually, but some drainages (Hoanib, Hunkab, Kharugaiseb and Samanab) are blocked by the Skeleton Coast dune field before reaching the sea (Fig. 1). Only exceptional floods, some recent examples related to a South Atlantic equivalent of the Pacific El Niño effect (Shannon *et al*., 1986), reach discharges high enough to breach this dune field through to the coastline. Patches of playa silts west of the present end-points of the Hunkab and Samanab rivers testify to previous periods when those rivers were able to penetrate further westwards more frequently (Lancaster, 1982; Vogel, 1989).

In 1995, a project was initiated to study the sedimentology of the Hoanib River (Fig. 1). One aim of this project was to identify and record the interaction between the Hoanib River in its lower reaches and aeolian dunes of the northern Namib dune field. This was in recognition of the importance given to differentiation of the deposits of such processes in units, particularly subsurface reservoirs, where rivers and aeolian dunes interact (e.g. North & Prosser, 1993). The Hoanib River was chosen to study the fluvio–aeolian interaction of such a dune-dammed ephemeral river system because the key area where the river interacts with the dune field is located in the conserved Skeleton Coast National Park and is thus little disturbed by human activity.

HOANIB RIVER DYNAMICS

The Hoanib river extends over a length of ≈270 km with a catchment area of about 17 200 km^2 (Jacobson *et al*., 1995), exposing granitic, calcsilicate, metapsammitic and metapelitic rocks of the Damaran Kaoko fold-thrust belt (Stanistreet & Charlesworth, 2001). East of the Skeleton Coast dune field, large parts of the catchment near Sesfontein (Fig. 1C) are covered by thick (up to 10 m) accumulations of wind-blown silty loess, most of which is resedimented by short-term rain wash. Petrography and TL dating of the calcareous silts suggested to Eitel *et al*. (1999) that the majority of the loess material originated from western Kalahari calcrete surfaces and accumulated during a more arid climatic period between 30 and 8 ka BP. At that time, both the offshore Benguela current and monsoonal influences from the north were suppressed, and higher amounts of aeolian dust were delivered to the area by strong easterly 'berg' winds from the continental interior. Since about 8 ka BP, slightly more humid conditions with episodic intensive rainfalls have been established in the eastern periphery of the Namib (Eitel *et al*., 1999). As a consequence, the modern Hoanib river has started to erode the loess accumulations, thus exposing them in badland surfaces and in river terraces up to 8 m above the present river bed.

Most of the recorded Hoanib river floods have ended in the extensive (8 × 4 km) and highly vegetated Gui-uin flood basin (Fig. 2) behind the natural dam of the Skeleton Coast dune field, where considerable quantities of laminated muds accumulate. Minor amounts of floodwaters percolate through the dune field, probably using fluvial notches cut into the underlying basement as groundwater channels. Groundwaters emerge at the western margin of the dune field and evaporate in vegetated, shallow salt-encrusted pools (salt vleis in Fig. 2). Only one flooding event per average of about 9 years has been

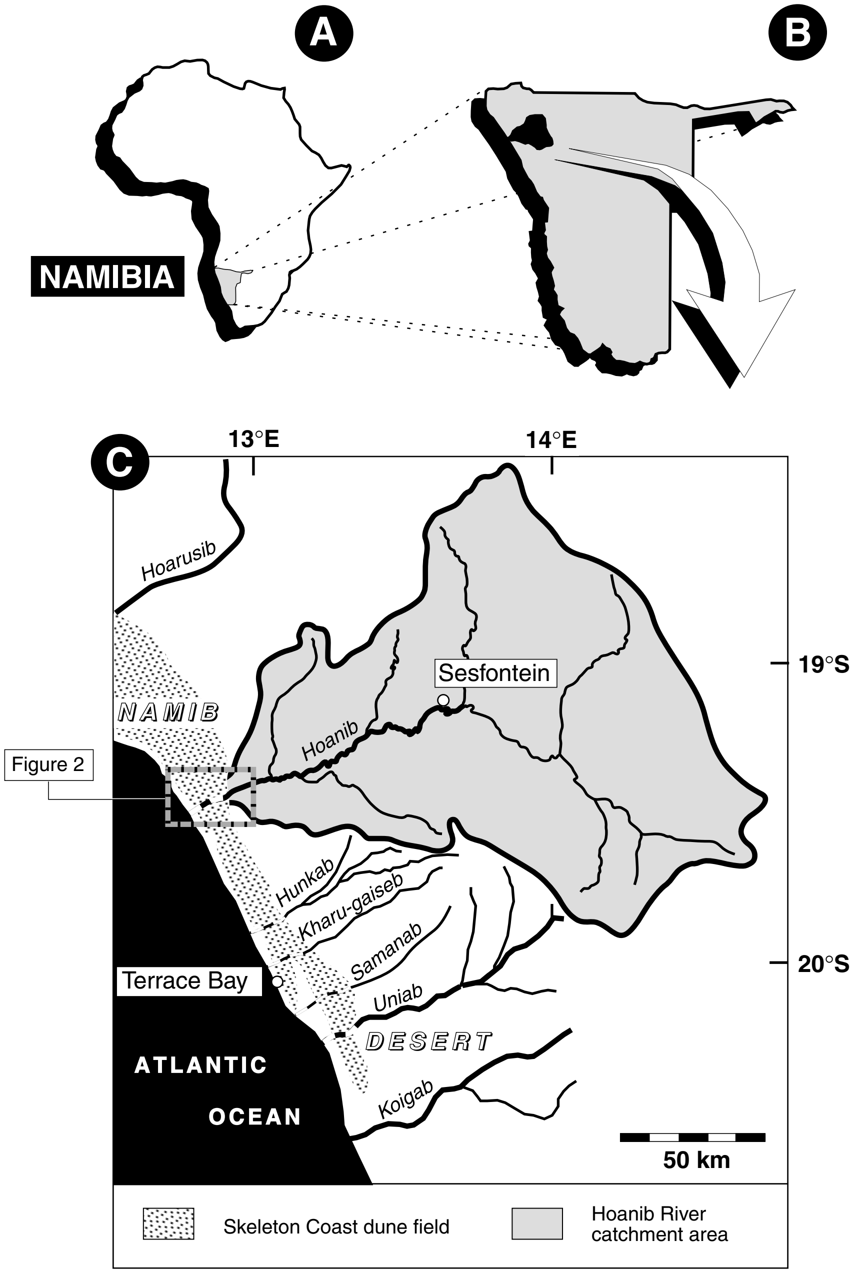

Fig. 1. (A and B) Geographical setting of the Hoanib River in NW Namibia with (C) showing the detailed location of the Hoanib catchment area in relation to the Skeleton Coast dune field.

observed to be large enough to break through the dune belt of the Namib Desert, although this has happened more frequently in recent years (personal observations and those of Nature Conservation staff at Möwe Bay). In such cases, the Atlantic Ocean, 20 km farther to the west, defines a base level for channel erosion, temporarily replacing the base level of the Gui-uin flood basin 200 m higher. Shifts in base level also promote the intensive erosion and fluvial incision into the previously described Holocene loess terraces (Eitel *et al.*, 1999), contributing to the suspended load of the river floods ponded downstream. Floods, including breaches of the dune field, may have occurred more frequently in northern Namibia as a whole during the last 8 ka, as evidenced by higher input of clays onto the shelf areas offshore from the Kunene River (Namibia's north-western border) mouth during the past 9 ka (Gingele, 1996).

During field seasons, the authors were fortunate to witness the after-effects of the major April 1995 and April 2000 floods and the more minor March 1997 flood, lasting only 2–3 days each. These events were probably caused by perturbations in the western Atlantic area of the tropical

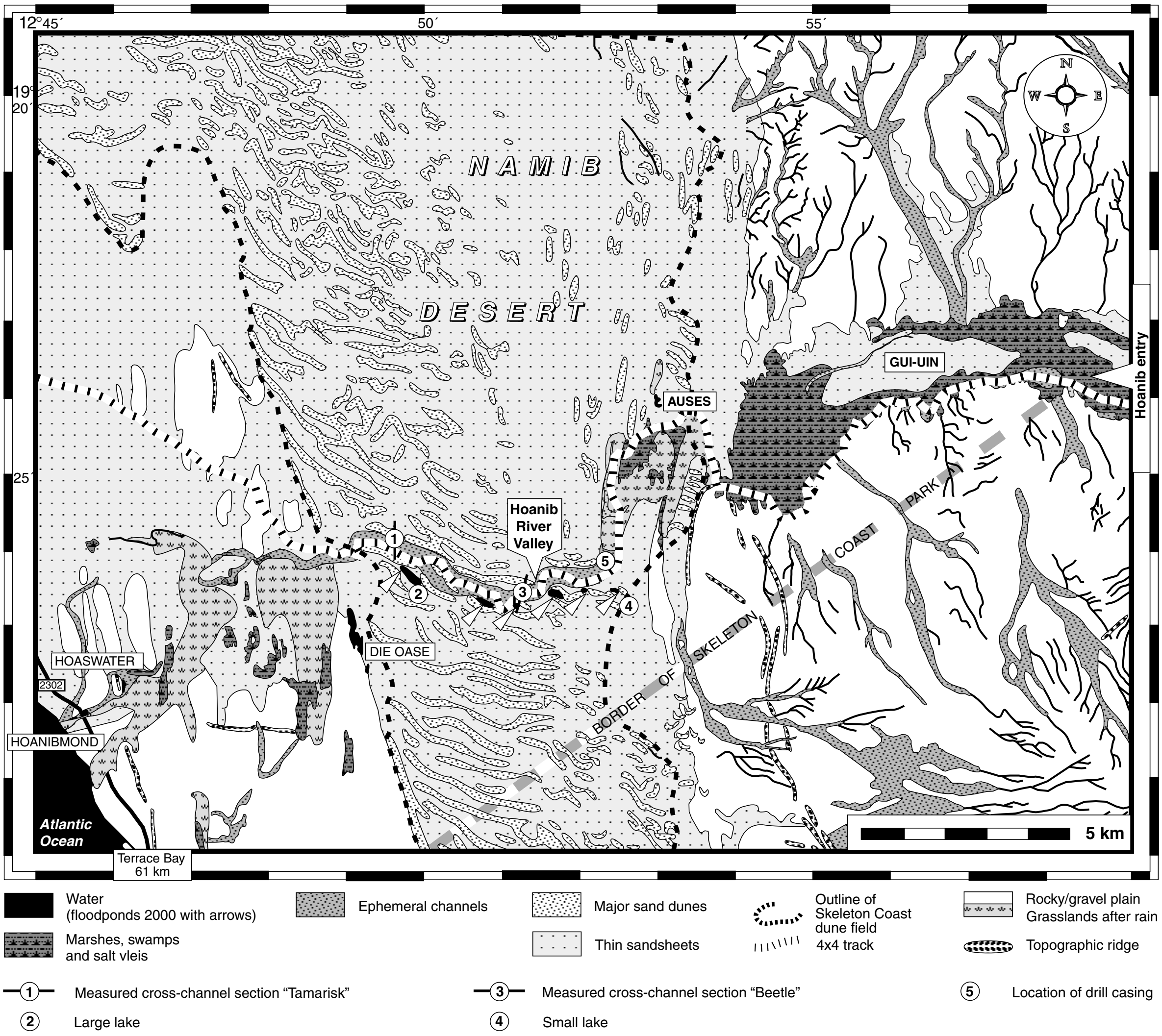

Fig. 2. Map of the area where the Hoanib river channel interacts with the Skeleton Coast dune field (based on Topographic map 1:50·000, sheet 1912BD Hoanibmond and LANDSAT TM 5-scene 181-074/074, band 4).

convergence zone over central Africa, possibly caused by disturbance there (Van Zinderen Bakker, 1984; Jury & Courtney, 1995; Jury, 1996), equivalent to those effects ascribed to the El Niño where they are incident against the western Pacific seaboard (cf. Shannon *et al.*, 1986; Waylen & Caviedes, 1987).

It was these specific climatic conditions that allowed studies on aspects of river flooding laterally into the interdunal corridors of the northern Namib Desert sand sea. This produced phenomena that provide a modern analogue, allowing: (1) understanding of aspects applicable to permeability disruption surfaces within aquifers and rock reservoirs; and (2) identification of the locus of river flooding through ancient aeolianite reservoirs, such as those of Permian–Triassic sequences of NW Europe.

FLOOD–AEOLIAN DUNE INTERACTIONS

A particularly impressive aspect of recent Hoanib River floods has been the way in which interdunes adjacent to the main river channel within the dune field have been used by floods as lateral ponds to accommodate excess water (Fig. 3). Many flood basins are close to the southern, windward side of the active fluvial channel; several filled presently are shown as lakes of various sizes on Fig. 2, but some are located a considerable distance (>1 km) away from the active channel. Flood ponds can achieve considerable size: one observed having lateral dimensions of 600 × 200 m, although an estimated average size is 100 × 35 m. The lateral flooding of interdune corridors would have had the effect of reducing flood discharge to a degree by

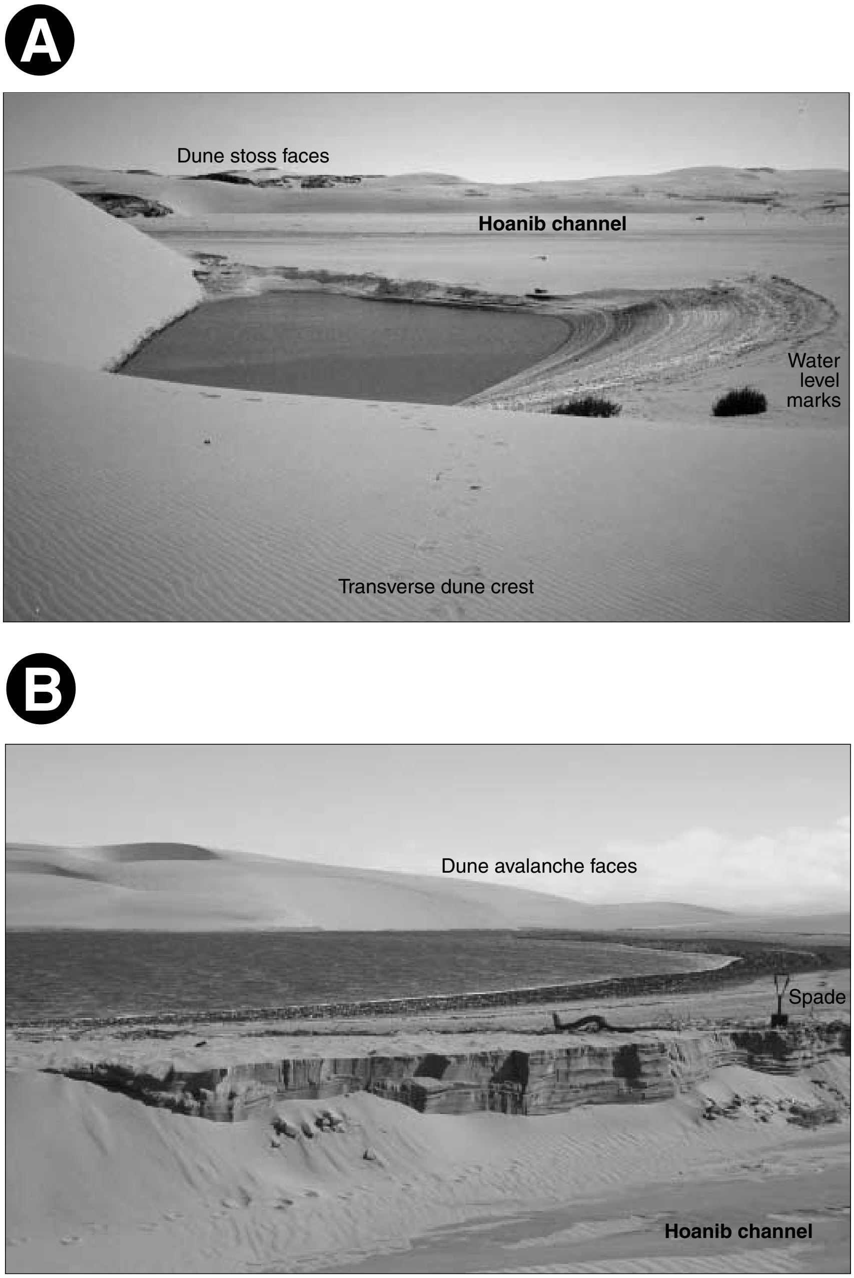

Fig. 3. Field photographs of Hoanib flood ponds. (A) At cross-channel section 'Beetle' (location 3 in Fig. 2), taken 4 weeks after the April 1995 flood and looking northwards into the flood pond (diameter is 25 m) and into the Hoanib channel behind. (B) At the 'Small lake' locality (location 4 in Fig. 2), taken 3 weeks after the April 2000 flood; spade for scale is 35 cm high, looking windward into the flood pond from the main channel over the end of an eroded dune remnant. Both flood ponds were located at the southern, windward bank of the Hoanib River. Water level marks indicated in (A) record the desiccation of mudstone layers generated by flooding of interdune areas.

diverting volumes of water away from the main channel conduit. In maintaining the natural flood ponds of the Hoanib River, there appears to be an intricate interaction between flood height, depression depth and the fines entrained with the incoming flood water. A similar process was mentioned in the broad review of aeolian bounding surfaces by Fryberger (1993) and studies of fluvio–aeolian interaction by Ahlbrandt & Fryberger (1981) and Langford (1989). However, Herries (1993) implied that flooded interdune deposits should show only vague contacts with associated aeolian cross-strata.

Dune morphology of the Skeleton Coast dune field is dominated by prevailing SSW winds, causing an increasing aggradation of dune sands above the coastal deflation surface in the downwind direction. During winter months, hot, easterly, high-velocity and lower frequency 'berg' (literally 'mountain') winds from the continental interior may also affect the complex dune systems. However, those modifications of the dune morphologies are usually confined to the dune crests (Lancaster, 1982, 1983), representing the portion of the dune with lowest preservational potential. The dominant aeolian bedform is therefore a WNW-trending transverse dune with considerable lateral continuity (Fig. 2) but some bifurcation along its length. At any one time, the Hoanib River uses mainly one particular interdune depression as the locus for its flow, modifying it to act as the main river channel. This results in a WNW-trending reach of the river, which is deflected 45° from the regionally average WSW river trend outside the dune field. After flooding and subsequent drying, preferential deposition of aeolian sediment occurs at the leeward (downwind) side of the channel route, favouring future flooding towards its windward side. The north-north-eastward progress of a dune downwind into the main channel (marked by the track in Fig. 2) therefore promotes gradient benefits for a new channel route through the next, windward interdune depression to the south. The effects of this benefit are shown by the development of a branch of the river, situated just to the north-east of location 2 on Fig. 2, that anastomoses around a dune. Observations over the period 1994–2000 indicate that this side branch is gradually becoming the main channel. Additionally, it appears that flood ponds are particularly numerous to the south of the river channel (Fig. 2), suggesting gradient-induced avulsion in that direction. This is a form of channel avulsion process not recognized in the presently understood spectrum of fluvial avulsion types. Its novelty derives from the fact that aeolian, not fluvial, processes predominate in controlling the avulsion effect.

Figure 4A is a river channel cross-profile within the dune field measured at position 'Beetle' indicated in Fig. 2. Measurements were taken by a theodolite survey 4 weeks after the April 1995 flood. It is evident that a dune avalanche face and another dune stoss face define the left and right river banks respectively. Still evident is an erosive notch (Fig. 4A) cut into the base of the channel-confining stoss face (right bank). In contrast, the channel-confining avalanche face of the windward left bank (Fig. 4B) has buried any erosive breach. Within the interdune area to the south of the river channel (Fig. 4B) lies a small flood pond cut by the line of our section, recording the water level in the pond at the time of measurement (Fig. 3A and 4B). The water depth within the flood pond was greater than 4 m. Also recorded in Fig. 4B is the height to which mud and wood debris was deposited on the pond's bounding stoss face, recording the maximum flood level in the adjacent main channel. From the maximum height of water referred to the avalanche face within the main channel, measures of water depth varied from 3·5 to 3·8 m.

The flood pond shown in Fig. 3A is a small example tens of metres in width, positioned on the section Beetle (Fig. 4B) at locality (3) on Fig. 2. Figure 3B shows a larger example viewed from the left side of the main channel, estimated at 300 × 200 m across, indicated at locality (4) in Fig. 2. The magnitude of a flood pond is dependent upon the geometry and size of the host interdunal area, and the largest so far recorded is pictured in Fig. 5A, estimated to be 600 × 200 m laterally in locality (2) on Fig. 2. In the case of all these flood ponds, the water height has fallen soon after the flood peak to expose a mud drape on the confining dune flanks. These are quickly covered by avalanche faces (Fig. 5B), but remain exposed for a considerable time on stoss slopes. Exposed mud drapes are covered by wood debris, up to the size of tree trunks, and other vegetation floated into the pond and left stranded, particularly on the downwind (northern) side. Highest parts of the mud drape display well-developed desiccation cracks (Fig. 5B) and, as the flood level retreats through evaporation, water level marks are developed (Fig. 3A). Other flood ponds are mapped adjacent to the channel in Fig. 2.

The largest of the flood ponds (location 2) has an extensive inflow delta (Fig. 5A) that was developed as flood water entered that interdunal area. A trench was dug into the equivalent inflow delta formed by the flood pond at locality (4) to reveal characteristic internal structures (Fig. 6). The sequence comprised sand displaying pondward-dipping foresets, overlain by plane lamination. This succession is reminiscent of that developed in subaqueous to subaerial washover fans formed in lagoons behind microtidal and mesotidal barrier systems (Schwartz, 1982). The formation of these structures is presumed to be equivalent: the foresets are generated by flood water entering the standing water of the flood pond itself, followed by subaerial shallow flows on top of the delta. Similar shallow flows and resulting structures are developed across the tops of fluvial sandbars (e.g. Smith, 1971).

Each inflow delta is accompanied by a shallow channel, situated along one side of it (Fig. 7A), characteristically along the edge where its downstream side attaches to the adjacent dune. A trench was dug along the axis of the channel, associated with the flood pond at locality (4). In the trench, the shallow channel sequence lies directly upon a thin mud layer (<1 cm) and

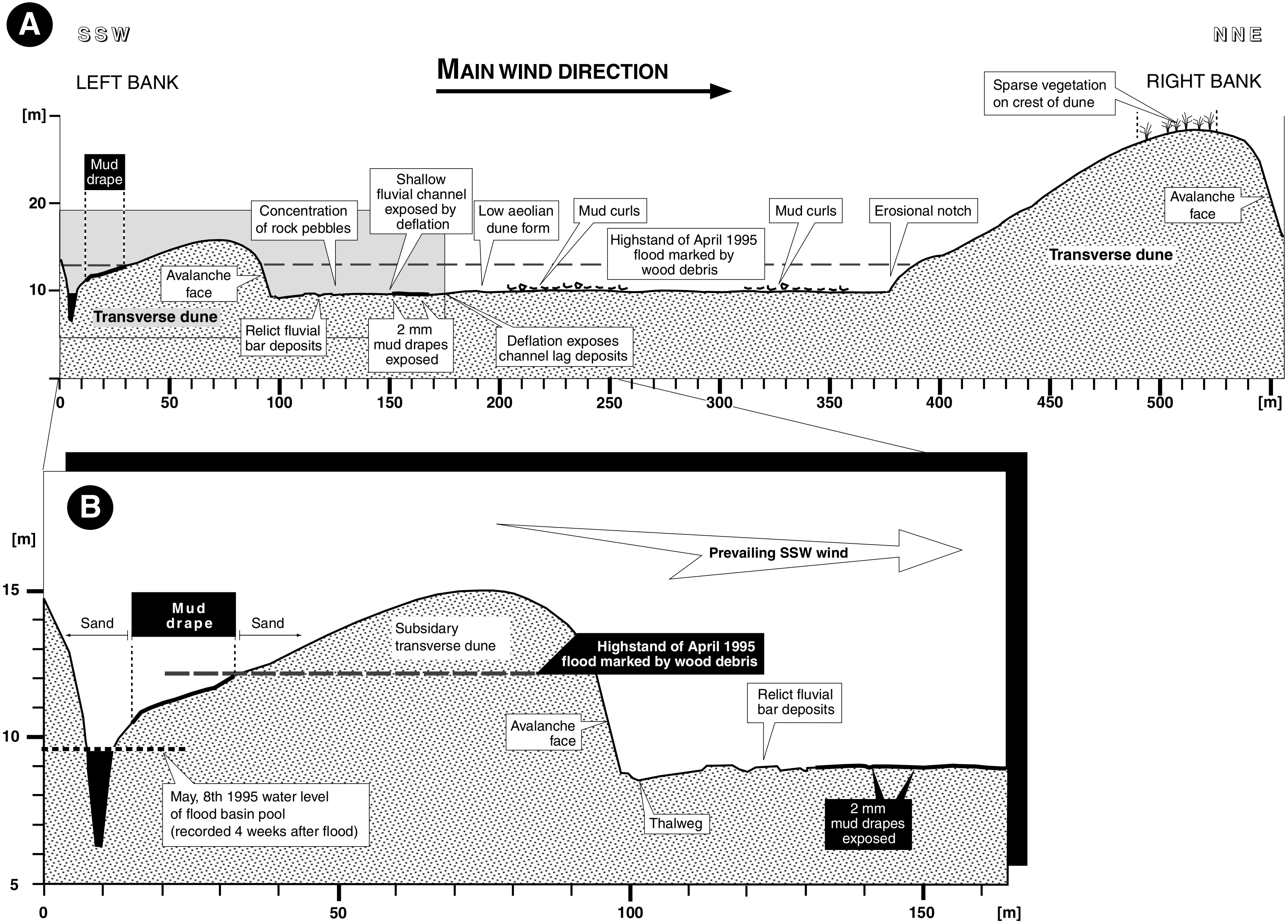

Fig. 4. Surveyed cross-sections at location 'Beetle' of the Hoanib River channel viewed downstream. (A) Cross-channel profile of section 'Beetle' (location 3 in Fig. 2), with all available information on flood water heights compiled. (B) Details of the interdune pond shown as enlarged inset, 10 times vertically exaggerated. The subsidiary dune indicated attaches to the main transverse dune defining the left bank of the Hoanib River channel.

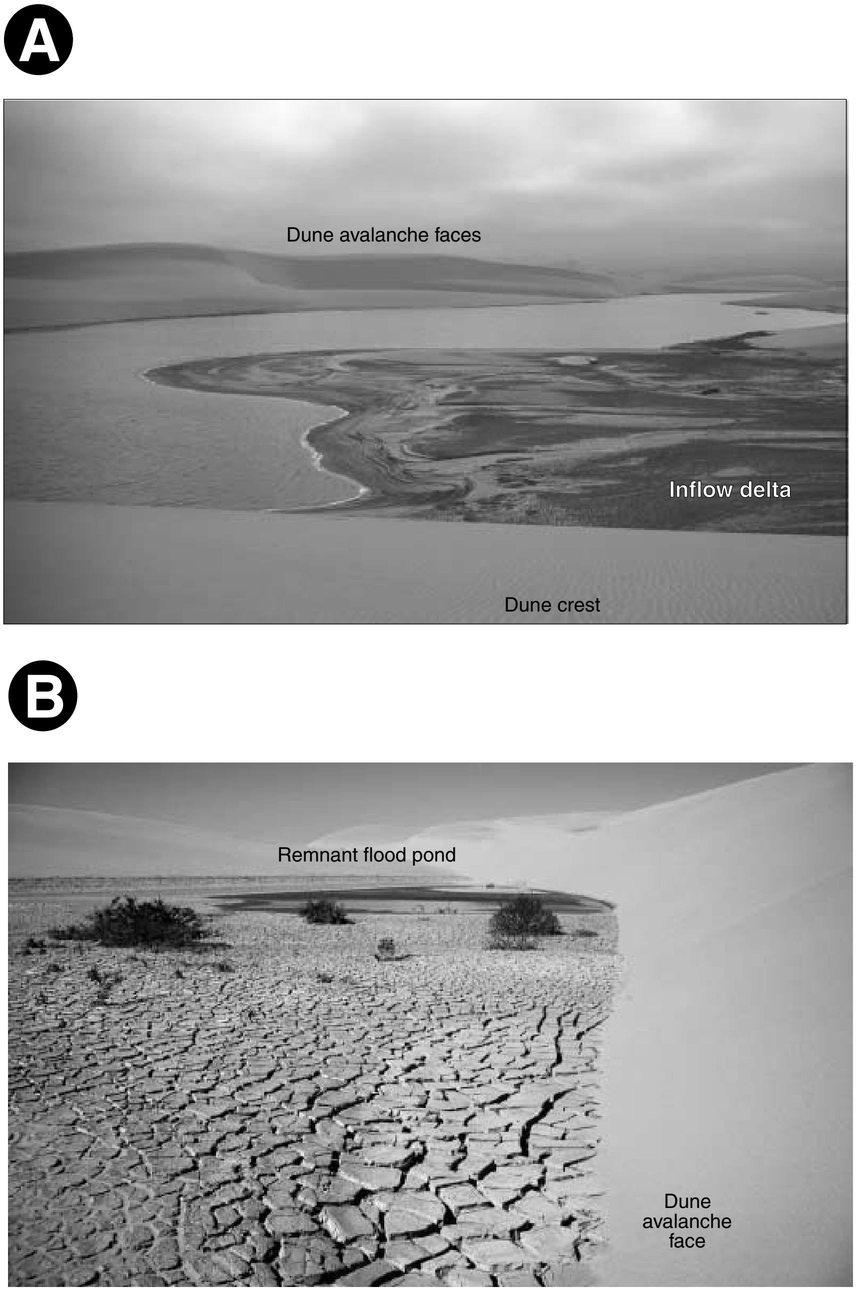

Fig. 5. Field photographs showing (A) oblique windward view (to the SW) of inflow delta (*c.* 100 m wide) at the 'Large lake' flood pond (location 2 in Fig. 2), 3 weeks after the April 2000 Hoanib floods. The Hoanib channel is towards the right outside the photo. (B) Burial of a mud-lined, nearly dry flood pond by a downwind-prograding dune avalanche front (location 3 in Fig. 2).

comprises ripple cross-laminated sands (Fig. 7B). Their structure is produced by migrating linguoid to sinuous-crested ripples, the form of which is still preserved at the surface within the channel (Fig. 7B) mantled by a thin mud drape. Flow was directed along the channel towards the main river, revealing its function as an outflow channel (Fig. 7A). Outflows back into the main channel relate to waning flood stages and lowering river levels, when pond water is potentially slightly higher than the river level. The outflow channel incises into the preceding inflow delta; thus, the delta ultimately acts as a barrier, damming the original flood access corridor and enhancing the ponding effect.

FLOOD POND EVOLUTION

The evolution of a flood pond can be reconstructed as having followed a series of stages, expressed in Fig. 8:

(A) Flood waters in the main channel promote a breach into adjacent interdune depressions along which water floods passively to form deep ponds (Fig. 8A).

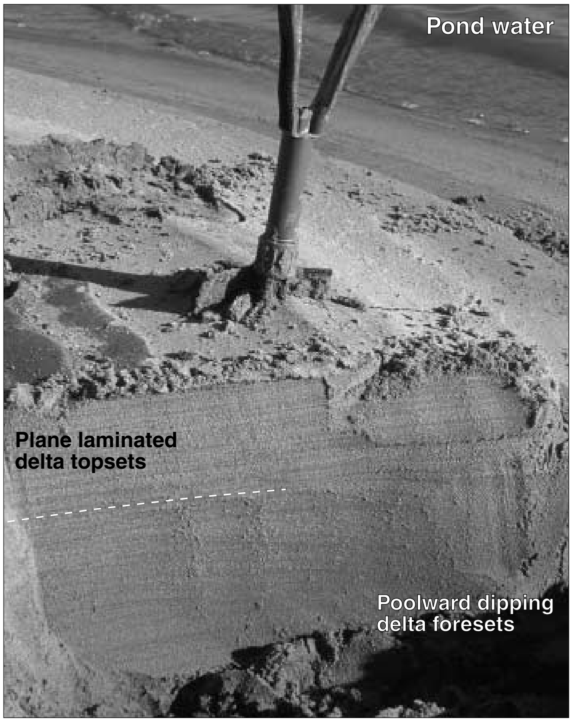

Fig. 6. Trench into the delta front at 'Small lake' flood pond (location 4 in Fig. 2), showing subaqueous inflow delta foresets overlain by plane-laminated delta topsets; the Hoanib channel is towards the left. The position of the delta front can be seen in the background with water lapping against it. The location of the delta front can also be seen in Fig. 7A, with the spade situated in the same position in both photographs.

(B) From the time water initially enters the interdune area, water seeps into the underlying sand at even, relatively high velocities (Crerar *et al.*, 1988). Seepage and infiltration of clay into pore space between the topmost sand grains of the substrate generate a very thin impermeable seal reducing infiltration to a negligible value (Wheeler *et al.*, 1987). Subsequently, fines settle in the stilled flood water to form a mud layer on top of the seal. The mud layer directly overlies the stoss face of the preceding and the avalanche face of the succeeding dunes that define the interdune area.

(C) Waning flow in the inflow area from the main channel deposits sand as an inflow delta prograding into the pond (Figs 5A, 6 and 8B), the delta enhancing the depth to which water can ultimately be dammed within the lateral flood pond by restricting water return into the channel.

(D) Water depth is reduced in the flood pond as a result of seepage, water return into the main channel and subsequent evaporation. The degree of water return is indicated by the height of mud above the base of the outflow channel shown in Fig. 3A. Higher parts of the flood pond are exposed to form desiccation cracks in the mud (cf. Fig. 5B). Return flow into the waning active river system excavates an outflow channel (Fig. 7A and B) through the inflow delta.

(E) The flood pond water level is effectively perched many, perhaps tens of, metres above the regional water table on top of the impermeable mud seal (Fig. 8C). The resulting temporary (>3 years) water body supports animals, particularly those living in marginal desert environments such as gemsbok (oryx) and desert elephant.

(F) Subsequently, evaporation proceeds to dry up the pond eventually, or the enhanced river channel admits subsequent floods, which might even be of lesser magnitude, to fill the already mud-lined hollow (Fig. 8B) and replenish the lateral interdune flood pond.

ANCIENT FLOOD PONDS ASSOCIATED WITH AN EARLIER HOANIB RIVER CHANNEL

Mud layers that are interpreted as recording ancient flood ponds have been exhumed in the northern (or right) bank of the main Hoanib river channel at cross-section 'Tamarisk' (Fig. 9) measured at location (1) in Fig. 2. Confinement of the main Hoanib river channel by the aeolian dune forms is evident. The south bank is provided by the avalanche face of the dune windward from the channel (Fig. 10A). The north bank is defined by the stoss face of the complementary downwind dune. Two mud layers bearing abundant desiccation features are partly exhumed on the north bank stoss face (Fig. 10B). They stand out as layers resistant to erosion varying between 2·4 and 4·5 cm in thickness and dip at angles of 30° and 34°. They are parallel and conformable with preceding and subsequent dune avalanche foresets also exposed by the stoss face. The stoss face of the right bank is particularly prone to erosional flood effects. Annual river floods following the historic April 1995 flood have consistently removed sand blown into the river channel from the windward dune (southern bank), thus depleting sand provision to the stoss face of the leeward dune (northern bank). This sand starvation may contribute to enhanced wind erosion on the stoss side of the leeward dune, exhuming a plan view of its own previous avalanche foresets as it proceeds in a northerly direction under the prevailing wind.

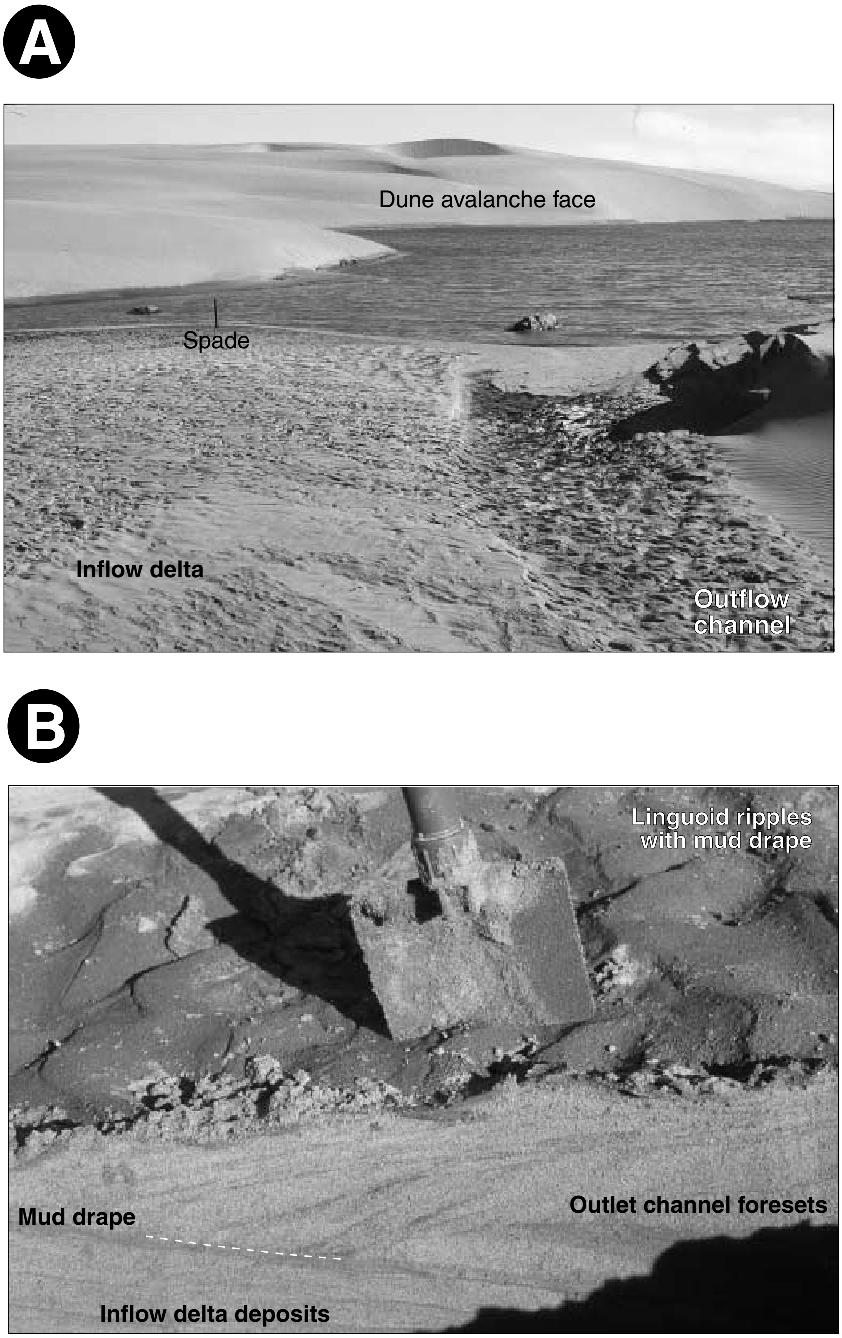

Fig. 7. (A) Arrangement of the outlet channel at the downriver side of the 'Small lake' inflow delta (location 4 in Fig. 2). Behind the flood pond can be seen its windward side confining dune, with a stoss face towards the viewer. The spade marks the front edge of the lobe-shaped inflow delta, whereas to the left of that can be seen the mud-draped outflow channel cutting down into the previously deposited delta deposits. (B) Trench illustrating outlet channel foresets directed away from the flood pond overlying an inclined flood pond mud drape; flood pond towards the right, Hoanib channel towards the left.

The extent of erosion of the right bank of the Hoanib is indicated at a position 3 km upstream from cross-section 'Beetle' (location 5 in Fig. 2). There, a drill casing protrudes from the channel floor, the lining of a water borehole drilled before the 1995 flooding. The borehole was drilled into the leeward (northern) river bank at a distance 10 m away from the main channel. The pipe now stands isolated in the middle of the main channel, 115 m from the present right river bank, indicating the large volume of sand that has been removed from the leeward dune by flood erosion since 1995, equivalent to approximately half the present channel cross-sectional width. Wholesale removal of such large quantities of sand were witnessed by Department of Conservation patrols before and after a flood.

The highly inclined mud layers exposed at cross-section 'Tamarisk' are interpreted as examples of fossil interdune flood pond deposits, equivalent to those described earlier. Their age would therefore be equivalent to the time taken

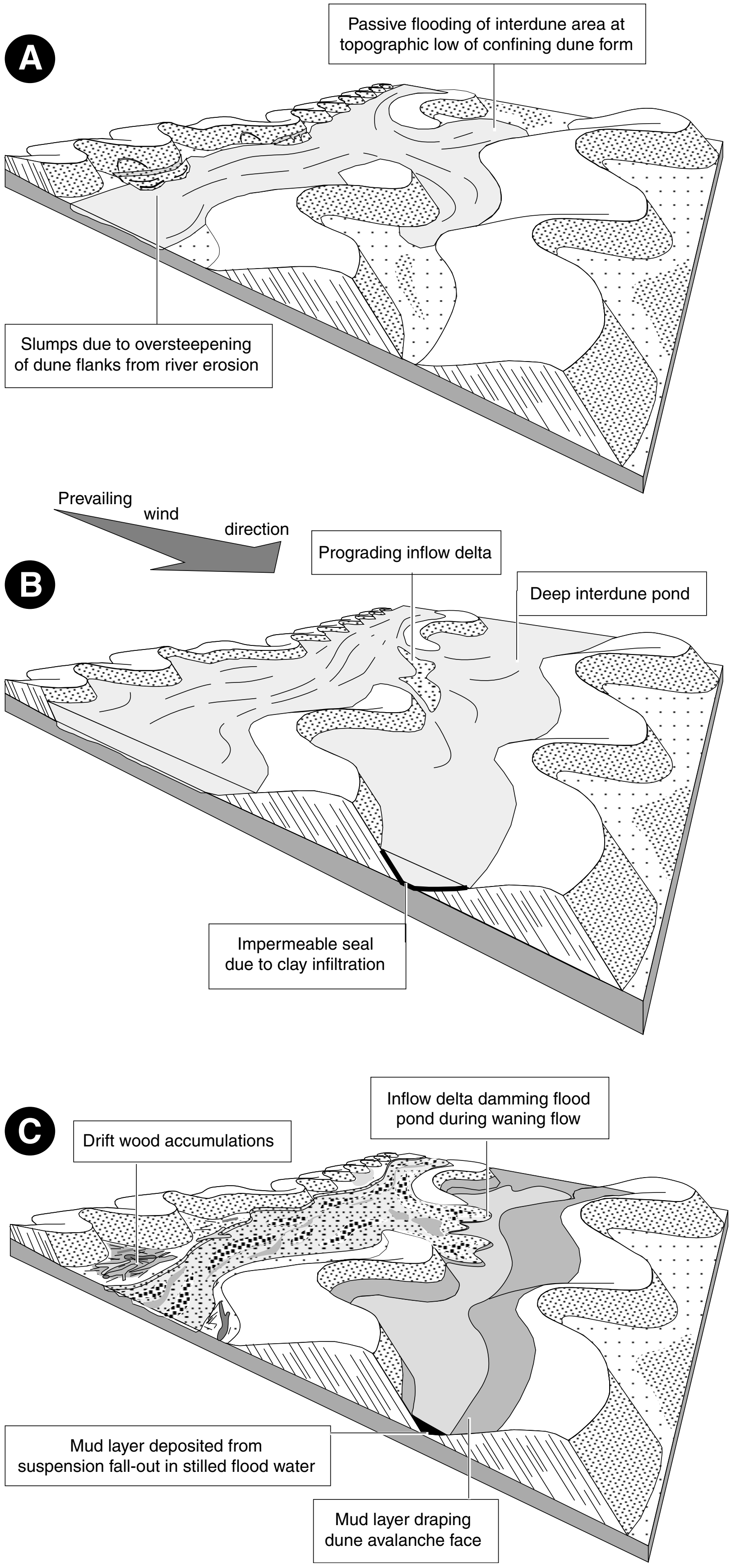

Fig. 8. Schematic stages in the evolution of a flood pond generated by fluvial interdune incursion. See text for further explanation.

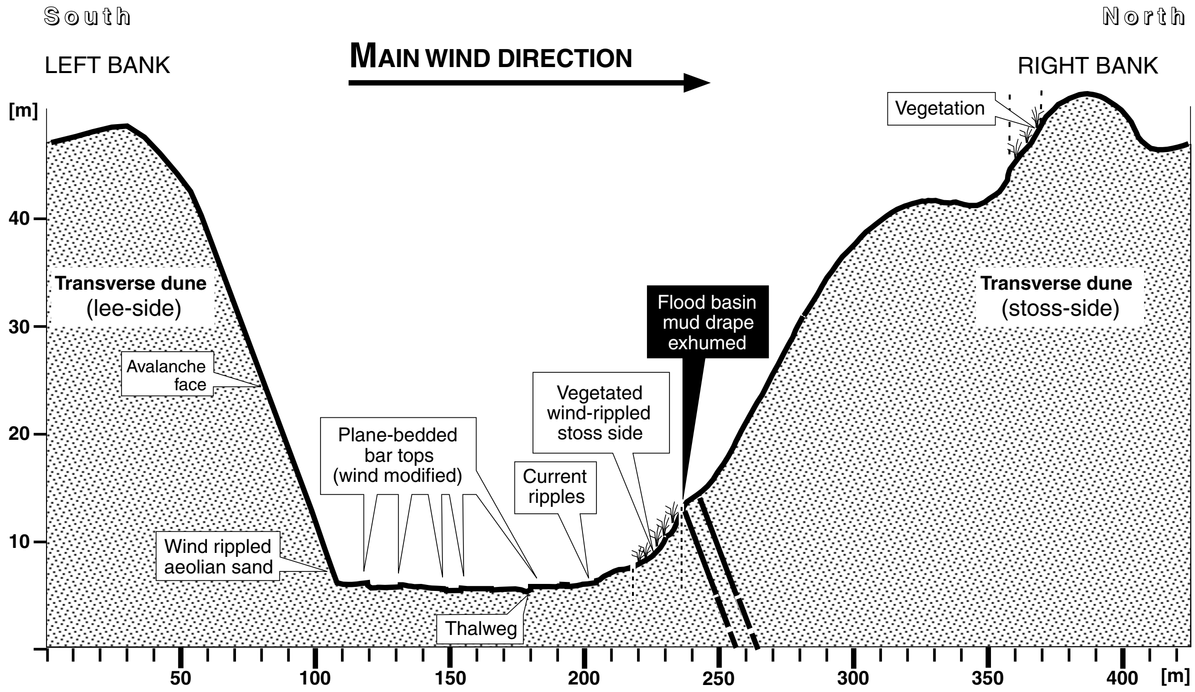

Fig. 9. Cross-channel profile of section 'Tamarisk' (location 1 in Fig. 2), which is 2·8 km downstream from section 'Beetle'. Mudstone layers of previous Hoanib river floods are exhumed on the windward slope of the right bank.

for the leeward transverse dune to have migrated a distance of approximately half a wavelength. That only two mud layers were exposed so close together on the lower part of the stoss face may result from the fact that a rare flood that breaks through the dune field prepares a deeper incised conduit that even lesser floods may use in any of the following years. Only aeolian transport and net deposition of sand within the channel, in competition with its fluvial removal, can eventually render the conduit less accessible to later floods. Thus, the first mud layer would probably have been deposited by the pioneer breakthrough flood and the second by a subsequent flood. The second of the flood ponds would have had not only the benefit of an incised river channel, but also the advantage within the interdune area of a prepared impermeable seal, on top of which the succeeding flood pond could perch. That no other mud layers were exposed on the lower stoss face may indicate how rare such breakthrough flood events may have been during the time it takes for a transverse dune to migrate its own half wavelength. Similar mudstone layers were exhumed by the recent floods in the ephemeral Hunkab and Uniab rivers (cf. Hüser *et al.*, 1998; Scheepers & Rust, 1999; Blümel *et al.*, 2000a,b), 45 and 97 km south of the Hoanib River respectively. These can be interpreted as analogue palaeopool deposits.

The higher frequency of flood breakthroughs during recent years (1989, 1995, 1997 and 2000) may indicate that aridity in the region is decreasing even if it is unclear whether these are long- or short-term effects. In this regard, the record of such mud layers may provide an index of changes in the climate of the western South Atlantic and of how El Niño-type conditions have affected northern Namibia in previous times.

DEGREE OF DISTURBANCE BY INTERDUNE FLOODS

Although intuitively it may be thought that floods into interdune areas should cause major disturbance of the neighbouring sedimentary surfaces, even including extensive erosion, this is clearly not the case concerning the fossil flood pond mud layers identified at Tamarisk section. The earlier mud layer is covered conformably by aeolian foresets, which then act as a floor to the succeeding flood pond that deposited the second mud layer. The flooding into the interdune might therefore be visualized as a relatively passive process. This can be achieved by 'overspilling' of the flood across the edge of the channel and into the interdune or, where more than one interdunal area is involved, from one interdunal area into its

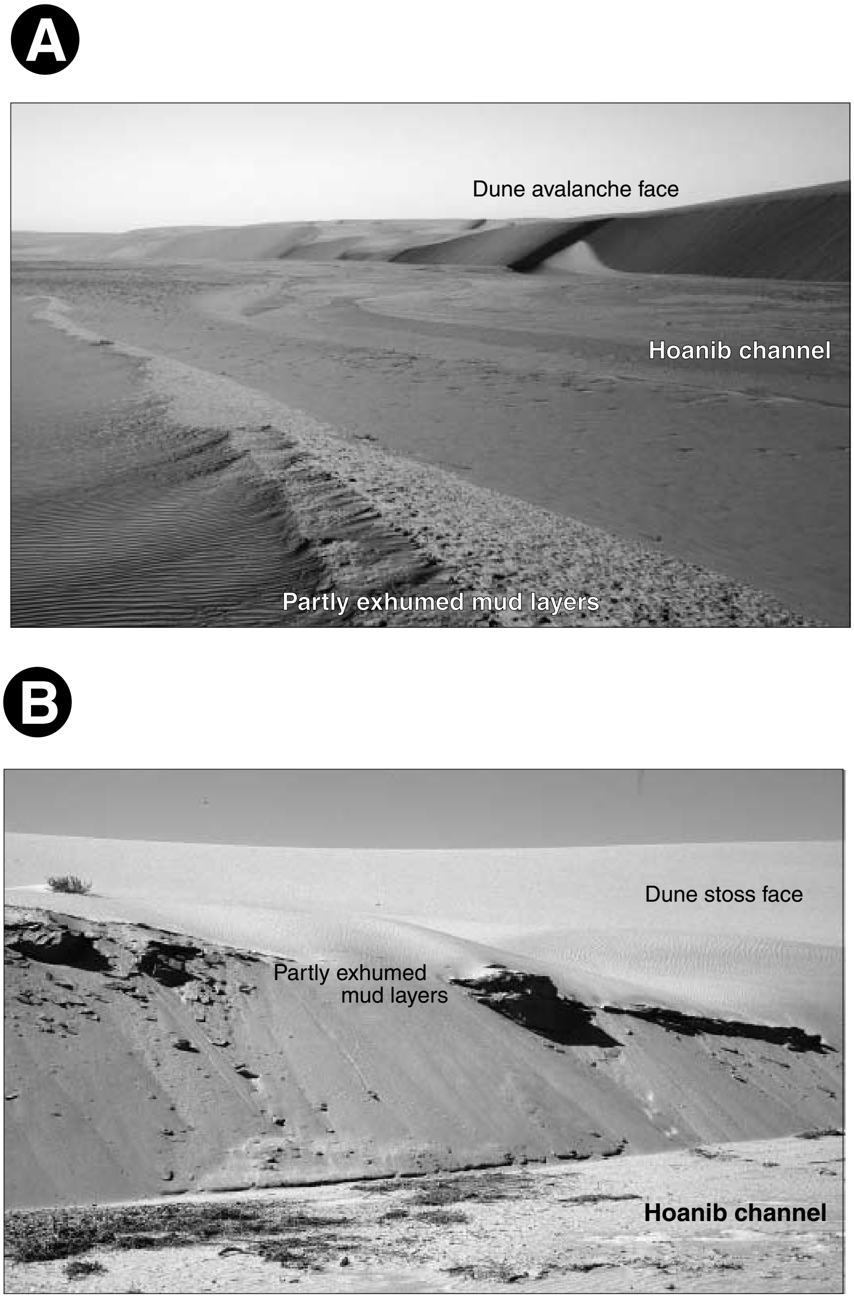

Fig. 10. (A) Overview photograph of channel morphology at section 'Tamarisk' (upstream view to the SE) with the prograding dune avalanche front of the southern bank of the channel to the right and the dune stoss face of the northern bank exposing two mudstone layers recording ancient flood ponds.
(B) Field appearance of the two mudstone layers exposed at the stoss side of a dune. Note the spreading of mud chips as a result of aeolian activity.

neighbour as described by Langford (1989). A process of overspilling has been recorded photographically in the case of ponding in interdune areas where the annual river flood of the Okavango river system of NW Botswana enters an area of aeolian dune forms at its distal end (Stanistreet & McCarthy, 1993). Although many of the details are different in the Botswana case, for example the Kalahari dune forms are presently inactive and the flood waters enter the area every year, the way in which ponding and overspilling can minimize disturbance of the interdune is well illustrated. Langford (1989) recorded floods ponding into erg margins, in contrast with the Hoanib and neighbouring rivers, which channel all the way through the middle of an active dune field. Langford (1989) has also recorded flooding of interdunes, but lower mud content in the floods that he recorded did not promote the perched ponding recorded here, but rather the sapping of dune strata and the flooding of adjacent unconnected interdunes.

INTERDUNAL FLOOD POND MUDSTONE LAYERS IN ANCIENT AEOLIANITES AS PERMEABILITY BARRIERS

An analogous ancient palaeoenvironmental setting to that described from the modern Hoanib River can be identified in the Permian–Triassic Kinnerton Sandstone, Sherwood Sandstone Group, of the Cheshire Basin, UK. At Burton Point (Fig. 11), mudstone layers have been identified interleaved with aeolian cross-beds of large set thickness, in sets otherwise interpreted as aeolian in origin (Fig. 12A). This was recorded by Herries in a diagram (Fig. 12B) presented by Thompson (1997). The mudstone layers are developed along 2 m of the uppermost part of the set, beneath a fluvial truncation surface.

Layers vary from more continuous to desiccation cracked and, in one case, polygons are developed as conspicuous desiccated mud curls. Little disturbance is apparent of underlying cross-strata, and overlying cross-strata lie conformably on the mud layer, infiltrating only underneath the mud curls. Significantly, the mudstone layer extends to the top of the preserved cross-set, the upper part having been eroded subsequently. Thus, such mudstones have the potential to extend across an entire more permeable interval within a sandstone reservoir. Considerable controversy has been generated concerning the proportions of the sequence deposited by either aeolian or fluvial processes. After the identification of predominantly aeolian processes by Thompson (1970), fluvial processes were invoked to a greater degree in the same localities by Oxnevad (1991). However, in ancient sequences that have experienced aeolian–fluvial interaction, on the evidence presented from the Namib, the presence of interleaved mudstone layers might sway judgement too far towards the involvement of fluvial rather than aeolian processes.

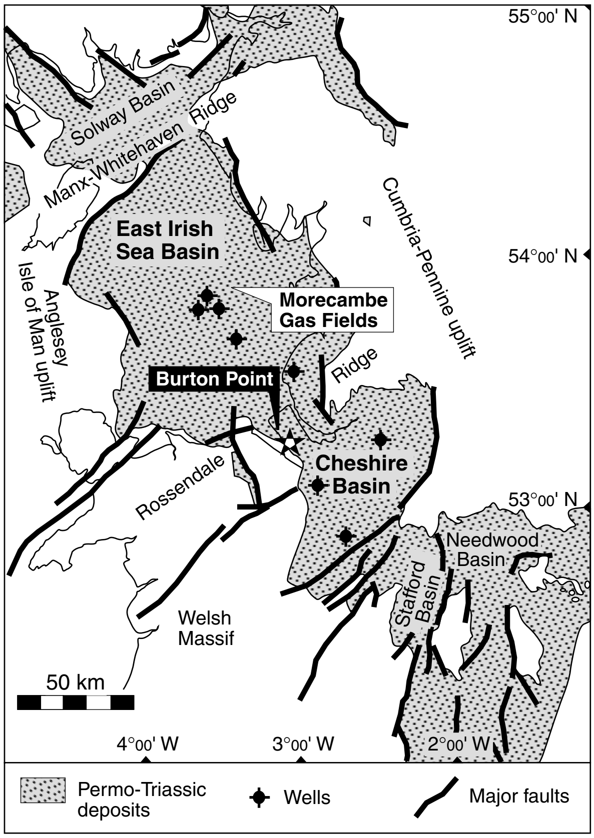

Fig. 11. Location of Permo–Triassic deposits, including the Kinnerton Sandstone Formation, basins and wells on- and offshore north-west England. Indicated is the position of the Morecambe Gas Fields, including well 110/2a-F1 mentioned in the text. Compiled from Jackson & Mulholland (1993) and Cowan (1993).

Where the Sherwood Sandstone Group is encountered as the major gas reservoir in the eastern Irish Sea Basin of the UK (Cowan, 1993; Meadows & Beach, 1993; Haig *et al.*, 1997), interaction between fluvial and aeolian systems has also been identified. Degree of dominance varies both stratigraphically and areally. Stratigraphically, climatic periodicity between arid and more humid conditions is thought to be the major controlling factor. Spatially, channel avulsion effects superimposed by regional structural faulting controls have dominated. Aeolian and fluvial facies associations in the Sherwood Sandstone Group are differentiated by Cowan (1993), but it is noted that some of the units classified as ephemeral fluvial channel deposits (for example his fig. 7: Box 36 – core at 3542·05 m) show a variation from mudstone layers apparently conformable with bedding to separated mud curls. These compare well with the mud layers described here from Hoanib interdunal flood ponds. Proportions of sequence produced by either fluvial or aeolian processes within the Sherwood Sandstone Group might be given a wrong weighting if mudstone layers are taken to indicate absolutely the fluvial nature of the associated cross-bed set. This is especially the case in core analysis, where such mudstone layers are particularly conspicuous.

Proportioning fluvial and aeolian deposition in sequences is important in the assessment of porosity and permeability variation (Haig *et al.*, 1997), both in the Sherwood Sandstone Group itself (Cowan, 1993; Haig *et al.*, 1997) and in other sequences showing aeolian–fluvial interaction

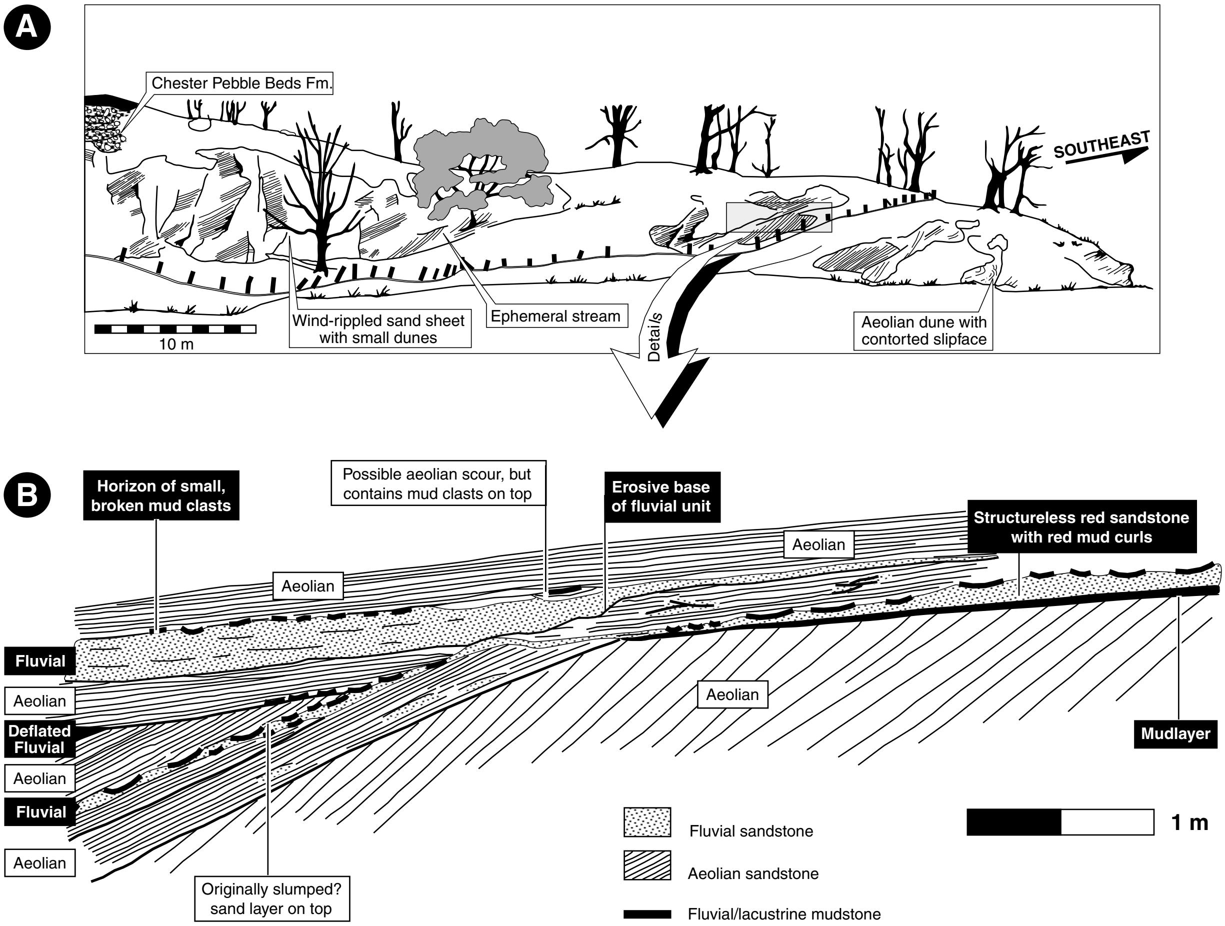

Fig. 12. Line drawings showing (A) the top of the Kinnerton Sandstone Formation at Burton Point, Cheshire Basin, UK (modified from Oxnevad, 1991) and (B) contact relationships of mudstone layers interleaved with aeolian cross-beds (original plot kindly provided by Rob Herries). See Fig. 11 for location of Burton Point.

(e.g. Langford & Chan, 1989, 1993; Ellis, 1993; Haig *et al.*, 1997; Jones & Blakey, 1997; Yaliz, 1997). This is emphasized by Herries (1993), who suggests that mudstones would not be likely to develop within the active erg, but that flooded interdune clay-draped reactivation surfaces would be more common close to the erg margin. In the case of the Hoanib River and other parallel rivers to the south (Lancaster & Teller, 1988; Teller *et al.*, 1990), however, fluvial events have flooded into the heart of the active Namib sand sea. Herries (1993) pointed out the way in which mudstones can compartmentalize reservoirs. Importantly, the mudstone layers described from the Hoanib follow the aeolian cross-stratification across an individual set. Although they are deposited only on the lower portion of an avalanche face (Fig. 13A), this is also that portion most likely to be preserved in the rock record in a reservoir (Fig. 12B). Sections in which floods have repeatedly ponded within interdunal areas may represent significant permeability barriers (Fig. 13B) within an otherwise more permeable portion of the stratigraphy.

In aeolianites, the mudstone layers themselves may be the most important piece of evidence that rivers have penetrated far into or have successfully broken through the active dune field. In the case of the Hoanib River, fluvial effects are represented chiefly by erosion of aeolian sand and would be represented in the record largely as omission surfaces. Flood effects, however, would develop a halo of mudstone layers around the main locus of river throughput or input, providing potential for a forensic reconstruction of its position. Such a halo would be spread laterally by the dune-controlled river avulsion mechanism referred to earlier and would represent a low-permeability zone within the otherwise aeolian-dominated unit. A halo of mud layers, relatively resistant to erosion, may also act as a stabilizing factor opposing long-term lateral channel

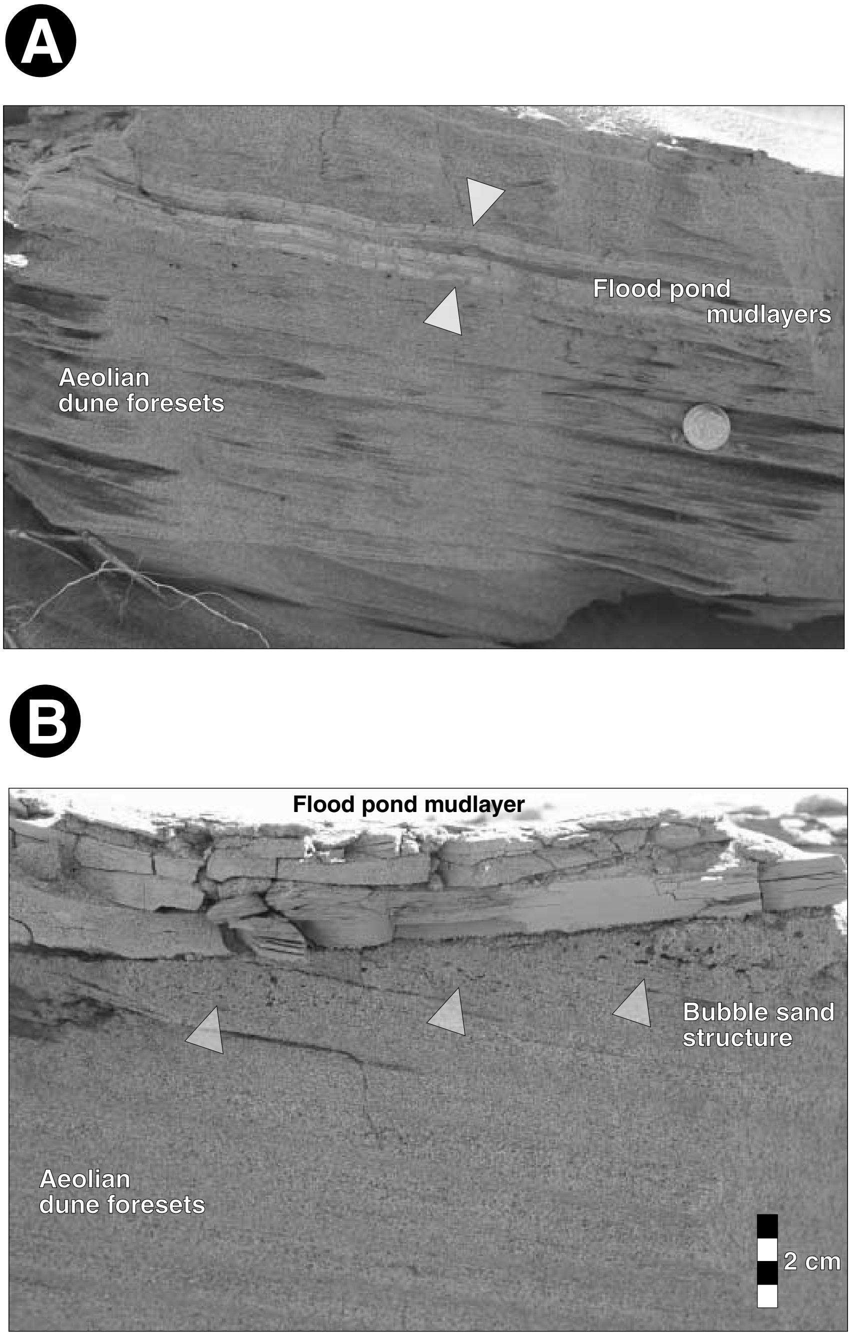

Fig. 13. Field photographs of Hoanib flood pond mud layers (A) draping dune avalanche face (coin for scale has 2 cm diameter) and (B) draping fluvially eroded top of aeolian cross-bed set developing bubble sand structure. These are produced by the entrapment of air bubbles when a river floods the dunes rather quickly before the rising groundwater table in the sediment reaches the surface. Such a rapid degassing process can contort or completely homogenize original aeolian bedding features (cf. Glennie & Buller, 1983).

migration. In this way, they would act in the way that mud-filled oxbows can act as a stabilizing influence on river meander belts.

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