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The Orange River, southern Africa: an extreme example of a wave-dominated sediment dispersal system in the South Atlantic Ocean

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Abstract: Sediments delivered to the South Atlantic Ocean by the Orange River are fractionated and dispersed northwards and westwards by a vigorous longshore drift system and a number of ocean currents. Gravels are accreted to the coastline for a distance >300 km north from the Orange River mouth. Sands are transported alongshore for >700 km but are, in places along this transport path, returned onshore by coastal winds to form the main Namib Sand Sea and other smaller dune fields. Mud is more widely dispersed westwards, northwards and southwards, probably by slow-moving, ocean-scale currents into basins on the shelf and onto the continental shelf edge. This dispersal system, operating since at least Eocene times, is believed to have originated during a time when there was a Late Cretaceous–Early Cenozoic uplift of southern Africa, which resulted in: (1) intensification of the existing southerly wind system; (2) incision of the Orange River, which, coupled with a shift in climate, resulted in a coarsening of its sediment load delivered to the coast; (3) a broad, weakly subsiding or mildly uplifting inner continental shelf with little accommodation space for the sediment load of the incising Orange River.

The western margin of southern Africa was formed during the northward, diachronous break-up of west Gondwana beginning in the Early Cretaceous from *c*. 127 Ma (Dingle *et al*. 1983). This event was preceded by a prolonged period of rifting, beginning in the Permo-Triassic (Lambiase 1989), that produced basins now seen in the offshore region, many of which were filled with sediment thinning to the east (Clemson *et al*. 1997). Remnant Permo-Carboniferous Karoo deposits onshore are mainly glacial–fluvial–deltaic, often with a palaeoflow to the west into what Martin (1973) and many workers since (e.g. Visser 1997) have seen as a substantial Late Palaeozoic shelf sea dividing southern Africa from South America. Drainage systems of probable pre-Late Carboniferous age, which were occupied by the Late Carboniferous glaciers, also flowed to the west (Martin 1982) and many of these exhumed valleys are occupied by rivers today.

In Early Cretaceous times, a new series of more regional base levels were generated by the opening of the South Atlantic, which is thought by some to have led to the subsequent development of the Great Escarpment and the incision of existing Atlantic drainage (Dingle & Scrutton 1974). Three major, post-rift depocentres off the west coast of southern Africa received the sediments brought westward by this drainage: the Orange, Lüderitz and Walvis basins (Brown *et al*. 1995; Fig. 1). The Orange Basin is thought to have been filled by two delta complexes. The southern palaeo-delta lay offshore of the present Olifants River mouth and was relatively short-lived (but see Stevenson & McMillan 2004, for an alternative interpretation), existing from 117.5 to 103 Ma. The other, larger and longer-lived palaeo-delta lay offshore of the present Orange River mouth, was established at *c*. 103 Ma and existed to *c*. 60–70 Ma. The basins were inverted in the Late Cretaceous–Early Cenozoic (Brown *et al*. 1995; Aizawa *et al*. 2000; Holtar & Frosberg 2000).

Present Orange River and coastal regime

With an area of *c*. 900 000 km^2, the Orange–Vaal drainage is at present the main sediment outfall for southern Africa (Bremner *et al*. 1990). From a principal source in the Drakensberg and Maloti Mountains it drains the interior plateau of southern Africa, the bulk of which is >1 km above sea level and in places reaches >3 km above sea level. En route to the Atlantic this drainage has been superimposed on a Pan-African coastal fold belt, in places >1 km high (Fig. 1). The incised Orange River is unusual for a drainage of its size in that it has, since Cenozoic times, carried sediment of up to boulder size to the coast. Most of the coarse sediment is derived from the western rim of the highly elevated southern African interior plateau, referred to as the Great Escarpment by King (1962). The principal rock types are sourced from the Mid- to Late Proterozoic Namaqua Metamorphic Complex, the Late Proterozoic Gariep Belt and the Neocambrian Nama group (SACS 1980; Frimmel 2000*a*, *b*). The most resistant and the most common clasts in the Lower Orange River deposits are tough quartzites derived from the Nama Group. Whereas the distance between source and sea for some of these local basement clasts is short (80–170 km), finer sediments, together with some gravel and associated diamonds, have a provenance >1000 km into the interior of southern Africa.

Two major suites of gravel-bearing terrace deposits are recognized along the Lower Orange River: an older, mostly Early to Middle Miocene-aged Proto suite and a younger, presumed Plio-Pleistocene-aged Meso suite (Fowler 1976; Corvinus & Hendey 1978; Pickford *et al*. 1995). The present Orange, a river with extensive dams and flood control, is transporting fine gravel, sand and silt–clay to its mouth, where it also flows above a buried channel cut *c*. 70 m below sea level (Murray *et al*. 1970). In its headwaters the annual precipitation is up to 1500 mm a^{-1} but, its middle and lower reaches cross a semi-arid and then an

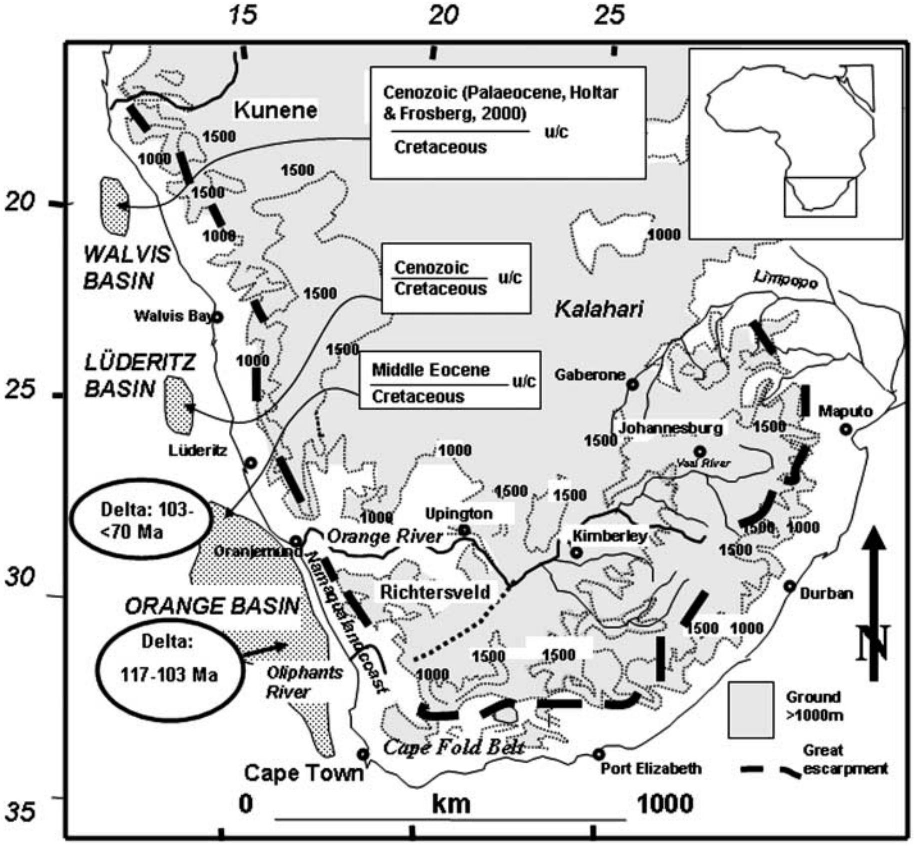

Fig. 1. Outline map of southern Africa showing the depositional basins on the continental shelf, the region of >1000 m elevation and the Great Escarpment. In addition, the ages of the sediments immediately above the top-Cretaceous unconformity within each basin are given, according to the few dates available.

arid region where the rainfall is often <250 mm a^{-1}. Although it is a perennial river, with a mean annual runoff of *c*. 11 km^3 and mean annual sediment load of 17×10^6 m^3 (Bremner *et al*. 1990), it is also subject to great variations in discharge (Zawada 2000). Peak floods reach 9000 m^3 s^{-1} but there have been times when reaches of the river have stopped flowing altogether (Bremner *et al*. 1990).

Although the tidal range is small (1.8 m at Oranjemund) the coastal regime and shelf off the southern African coast and into which the Orange River drains is impressive for the persistent wave energy, which is considered to be the most consistent in the world (Hay & Brock 1992). Imposed on a long period South Atlantic, SW swell (swell height >3 m) are shorter period waves, 90% of which have a height falling within the range 0.75–3.25 m (De Decker 1988). These are the response to a persistent SW wind, generated by the South Atlantic anticyclonic system and modified by a less frequent, reversing wind. Wave base is thought to be at a depth of *c*. 40 m although, as indicated by semi-submersible (JAGO) dives, the wave base can be considerably deeper at *c*. 110 m depth. Under present-day regimes, average waves are theoretically capable of transporting very coarse sand to depths of 30 m and post-storm waves can transport medium pebbles at the same depth. Cobbles are transported at *c*. 15 m water depth and during storms the inner shelf (30 m depth) is likely to be subject to extreme sediment transport (De Decker 1986, 1988).

That portion of the present submarine shelf extending down to 150 m water depth can be traced for *c*. 700 km along the coast between the Orange River mouth and Walvis Bay, and averages *c*. 60 km wide (Goslin & Sibuet 1975). The shelf width down to 200 m (e.g. during the last glacial maximum, when sea level was at −120 m and wave base at −200 m, relative to present-day sea level) reaches a maximum width of 150 km (Fig. 2).

Pleistocene to present dispersal of sediment

From studies of present-day and Pliocene–Holocene sediments it is evident that the wave energy existing on the inner shelf and coast is capable of separating the sediment delivered by the Orange River into size fractions. This wave energy, coupled with a potent northward-directed longshore drift, disposes of each fraction into geographically separate regions of shelf and shore (Fig. 2).

Gravel

A series of Late Pliocene to Holocene gravel beaches were, as a result of alluvial diamond mining activities, partly exposed along the coastal strip for *c*. 300 km north of the Orange River mouth (although the gravel extends *c*. 350 km in total; Hallam 1964). Studies of extensive sections of these beaches led to the conclusion that there was a gradual northward change in their morphology and grain size from often boulder-bearing spits and barrier beaches in the south, near the mouth of the ancestral Orange River, through extensive linear beaches to mainly pebble-bearing, pocket beaches in the north. This change is thought to have been controlled by a northward decrease in the rate of sediment supply in a vigorous longshore drift system (Bluck *et al*. 2001; Spaggiari *et al*. 2006). Gravel beaches have been located offshore and submerged wave-cut rock platforms have been found at depths exceeding 75 m (Murray *et al*. 1970).

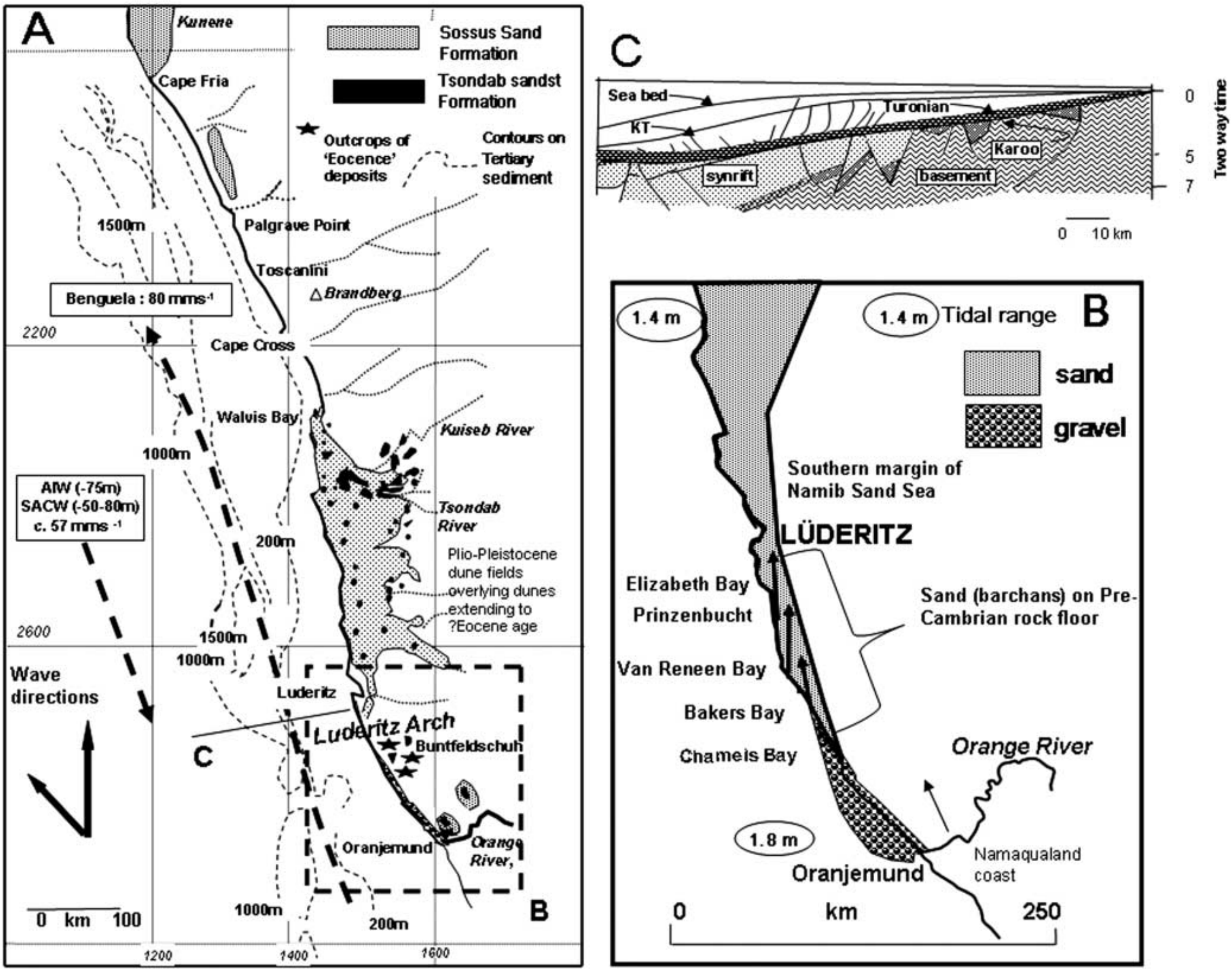

Fig. 2. Dispersal of sediments at the mouth of the Orange River and northwards along the coast. (**a**) Distribution on land of post-Cretaceous sediments and dated and probable Eocene deposits. Offshore contours show the thickness of Tertiary sediment (Aizawa *et al*. 2000). Current and wave-orientation data are shown, together with post-Pliocene sediment dispersal paths along the Namibian coast (see text for sources; AIW, Arctic Intermediate Water; SACS, South Atlantic Central Water). Locations of (**b**) and (**c**) are shown. (**b**) Distribution of sediment along the Namibian coast and positions of sand take-offs to the Namib Sand Sea. (**c**) Interpreted geo-seismic section based on Aizawa *et al*. (2000). KT, Cretaceous–Cenozoic unconformity of the inner shelf. Two-way time is in seconds.

Sand

The sand fraction moves in a subtidal to intertidal, drift-dominated zone generally <3 km in width, and is traceable northwards from the Orange River mouth to beyond Walvis Bay (Corbett 1996; Fig. 2), a distance along the coast of *c*. 700 km. North of Chameis Bay, where alternations of quartzite and schist bedrock strike almost north–south, there are a number of bays with headlands on their southern margins (Fig. 2b). These headlands initiate wave refraction, which serves to pile the northward-moving sediment into the bays immediately north of them. From these bays the strong onshore winds remove sand from the intertidal zones to the onshore, where they form a number of linear zones of aeolian barchans, or aeolian transport corridors (Corbett 1993), with some dunes moving at rates up to 100 m a^{-1} (Corbett 1996). These aeolian transport corridors are traceable to the large dune complex of the main Namib Sand Sea, where Lancaster & Ollier (1983) have estimated 3.73×10^{11} m^3 of sand to have accumulated as the Sossus Sand Formation (SACS 1980; Fig. 2a). Rogers (1977) considered this sand sea to be largely the 'displaced delta' of the Orange River.

Although the underlying, palaeo-dune systems of the Tsondab Sandstone Formation and associated sandstones may have contributed to the current Namib Sand Sea (*sensu* Besler & Marker 1979), the bulk of the sand making up the Sossus Formation is derived from the Orange River via coastal processes along the coastline to the north of it (Rogers 1977; Lancaster & Ollier 1983). Although the lower age limit of the Namib Sand Sea has yet to be determined accurately, estimations place this boundary as likely to be no older than Pliocene (Ward 1987; Ward & Corbett 1990; Pickford & Senut 1999).

Clay

From observations made today along the SW African coast and from studies of older continental deposits in the Namib, it is evident that little of the river-transported, coastal clay fraction returns to land. Observations made after major flooding of the Orange River indicated to Bremner *et al*. (1990) that clays were, however, temporarily stored in the nearshore zone only to be then transported elsewhere when suitable conditions arose.

With the bulk of the clay remaining in the sea, there are a number of possibilities for its retention there. In the coastal-shelf realm there is a greater range of slow-moving currents, some of which are oceanic in scale whereas others are secondary currents responding to the water-mass movements of the more powerful currents responsible for transporting the coarser sediment. This results in fine sediment being dispersed over a far wider area offshore than the coarse counterparts. Bremner & Willis (1993) pointed out that, apart from the Benguela current, the South Atlantic Central Water (SACW) as well as Antarctic Intermediate Water (AIW) are both involved in the dispersal of clays along the SW African coast. This allows the clay fraction delivered to the coast to be dispersed over a wide area and to accumulate in thick sequences in areas of available accommodation space (Fig. 2).

Between areas of basement bedrock or Cretaceous footwall, seismic sections (Clemson *et al*. 1997; Aizawa *et al*. 2000; Fig. 2c) demonstrate a comparatively thin layer of Cenozoic–Recent sediment draping the shelf between Walvis Bay and the mouth of the Orange River. The age of the earliest Cenozoic sediment has been established as late Early Palaeocene by Holtar & Forsberg (2000). However, fine, terrigenous sediments of roughly this age are believed to have accumulated to some thickness on the shelf edge (Clemson *et al*. 1997; Aizawa *et al*. 2000; Fig. 2c), some as contourites (Bagguley & Prosser 1999), and to the north in the Walvis Basin (Holtar & Frosberg 2000), where they exceed 1000 m in thickness. There is debate about the source of this clay-rich sediment, Diester-Haas *et al*. (1988) believing that it lies in the Orange drainage whereas Bremner & Willis (1993) suggested a source in the Kunene (Figs 1 and 2a). A 700 km long plume of clay-rich sediment, with a source in the Orange River, also extends to the south (Rogers & Bremner 1991) and is thought to be one of the significant routes for the dispersal of its clay fraction.

Summary

In summary, sediment brought down to the coast by the Orange River during the Plio-Pleistocene has been fractionated extensively in the vigorous littoral Atlantic environment. Gravel has accreted to the various Plio-Pleistocene shorelines, ranging in elevation from 30 m above and 120 m below current sea level. Most of the sand fraction has been absorbed by the main Namib Sand Sea, an area of *c*. 34 000 km^2. The clay and silt, although retained within the marine environment, accumulated ultimately along the shelf edge or over 700 km north in the Walvis Basin.

Age and evolution of the system

The Orange River and its sediment dischage

Dominating the post-rift evolution of the Atlantic passive margin of southern Africa has been the behaviour of the Orange River and its ancestral courses. Seen on seismic lines and confirmed by a number of offshore boreholes, a major Late Cretaceous deltaic complex is located offshore from the mouth of the present Orange River (Brown *et al*. 1995; Aizawa *et al*. 2000; Fig. 1). This delta, referred to informally here as the Kudu delta, is sand- and mud-dominated with nearshore and coastal dune complexes preserved in its basal deposits, and with remains of plant material and brackish-water faunas suggesting a major fluvial outfall at that time. There is also a strong marine influence in the macrofauna and deposition in a deltaic shoreline containing coastal barriers is suggested (Wickens & McLachlan 1990). Dingle & Scrutton (1974) linked this delta system to the Orange River drainage, and the incised meander loops of the lower Orange River may represent an inheritance from this Cretaceous drainage.

Further to the south, off the Namaqualand coast of South Africa, older deltaic complexes have been identified and a dominant outfall has been suggested roughly in the region seaward of the present Olifants River (Fig. 1) by Brown *et al*. (1995) and de Wit *et al*. (2000). Although not on the scale of the Kudu delta, the sediments here are coarser, quartz rich and were deposited in intertidal and shallow subtidal conditions along a high-energy coastline (Brown *et al*. 1995). More recently, the presence of this delta has been disputed by Stevenson & McMillan (2004), who interpreted a Late Cretaceous, palaeo-Orange River outfall to be represented by incised valley channels offshore of the Kleinzee–Port Nolloth sector of the Namaqualand coast.

The coastal energy and longshore drift system

The earliest evidence for an ancestral SW wind system along the Namibian coast is found in the aeolian Etjo sandstone, basal to and interbedded with the Lower Cretaceous Etendeka lavas dated at *c*. 127–137 Ma (SACS 1980; Turner *et al*. 1995). A dominant SW wind was also recorded in the Lower Cretaceous aeolianites intersected at the base of several deep boreholes drilled offshore into the Kudu delta (Wickens & McLachlan 1990). Onshore, the oldest Cenozoic aeolianites, also deposited by predominantly SW palaeo-winds, are those exposed at Buntfeldschuh (Middle Eocene age, Siesser & Salmon 1979; SACS 1980). Younger, mostly Middle to Late Miocene ages have, on the basis of faunal comparisons, been assigned to the upper levels of the Tsondab Sandstone Formation and its southern Namibian equivalents, all of which accumulated under south-quadrant wind regimes (Martin 1950; Ward & Corbett 1990; Pickford & Senut 1999). The Fiskus aeolianites, now dated as Pliocene, were deposited by south-quadrant winds, which even today dominate the Namib desert, where the Sossus Sand Formation and its lateral equivalents in Namaqualand accumulated (Ward & Corbett 1990; Lancaster 2000). All these aeolian sands have a wind palaeoflow from the SW and clearly imply a consistency and a possible continuity in wind directions for at least 42 Ma and possibly >130 Ma.

The Eocene Buntfeldschuh sequence: a change from a sand-dominated to a gravel-dominated coastline

The Middle Eocene sequence in the region of Buntfeldschuh (Fig. 2a) is critical to the dating of the change from a Late Cretaceous sand-dominated sequence to a gravel coastline. Here, some 150 km north of the Orange River mouth, in a down-faulted section, cross-stratified shoreface sands and probable storm-generated gravel sheets rest on metamorphic basement of the Late Proterozoic Gariep Belt (Fig. 3). These deposits are overlain successively and gradationally by beach sands interfingering with dune sands. Palaeocurrents in both shoreface and dune sands have a north to NW transport direction. This sequence of environments is remarkably similar to those seen in some of the offshore–onshore sections of the present coast and in some of the Pleistocene deposits exposed by mining along this coastal strip (Bluck *et al*. 2001) and documented by Pether

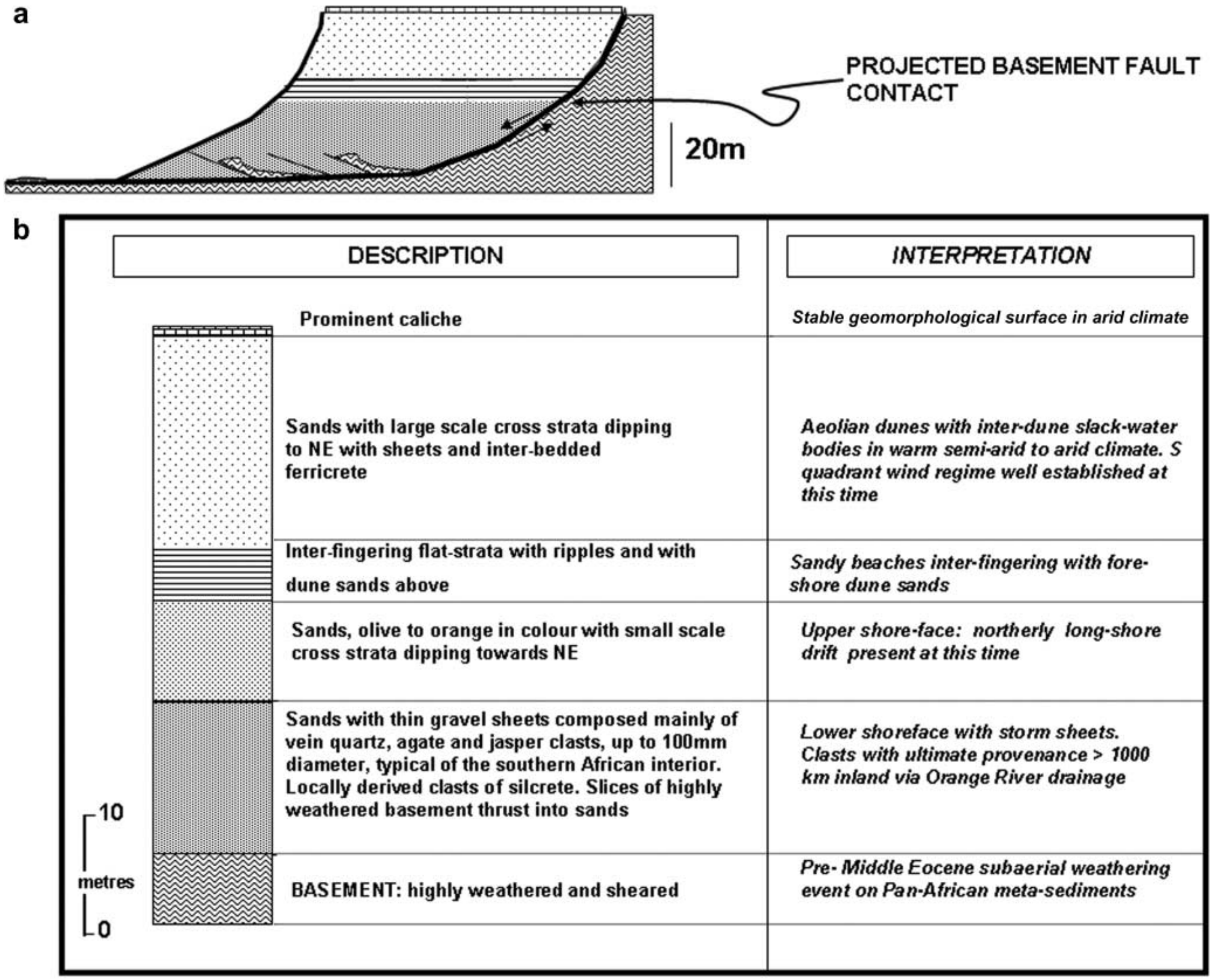

Fig. 3. (**a**) Diagrammatic cross-section of the exposure of the downfaulted, Middle Eocene sediments at Buntfeldschuh. (**b**) Measured section with description and interpretation of the Buntfeldschuh section. Intertidal sands interfinger with dune sands, showing that coastal dune fields were coeval with beaches.

(1994) further to the south in Namaqualand. Megaripples occur at present in water depths to *c*. 15 m (De Decker 1988), and these grade through a sand beach to onshore areas of sporadic or extensive dune sands, all with a northerly transport direction.

The gravel here, in scattered outcrops in the area around Buntfeldschuh and at the Orange River mouth (Figs 2a and 3), is distinctive in that it contains characteristic clasts of agate and distinctive yellow chalcedony, up to 100 mm in diameter, together with clasts derived from the Richtersveld. The agate–chalcedony assemblage is similar in composition to the gravels currently associated with both the Upper Vaal and Upper Orange drainages, >1200 km farther inland. Their occurrence at the coast is attributed to an accelerated Late Cretaceous to Early Cenozoic uplift and probable westward tilting of southern Africa, an event that is well recorded in the offshore (Brown *et al*. 1995; Aizawa *et al*. 2000). This change in river gradient was sufficient to transport coarse sediment to the coast, in contrast to the situation where fine sediment had been transported to and had accumulated at the coast in Cretaceous times when the Kudu delta formed.

Implications for the uplift of southern Africa

The Middle Eocene sequence exposed around Buntfeldschuh *c*. 150 km north of the mouth of the Orange River (Fig. 3), has four major implications for the uplift of southern Africa and associated evolution of the Orange River sediment dispersal system.

First, a substantial part of the Orange River drainage was entrenched by at least Middle Eocene times and most of its channel length was therefore fixed in its present position by that time. This is confirmed by the presence of basement clasts in some of the gravels, which suggests that the river had cut through the overlying cover. The present Orange River is estimated to be incised by *c*. 1 km through the Richtersveld (Fig. 1) and most of that incision is thought to have occurred during the Cenozoic.

Second, the middle and lower reaches of the Orange River were incised into (superimposed on) local basement (e.g. Maske 1957; Wellington 1958; Fowler 1976), a process that is likely to have commenced on a Karoo cover, remnants of which are still preserved in the Orange and related valleys (Helgren 1979;

Martin 1982; Wanke *et al.* 2000). However, much of the Karoo cover was likely to have been eroded off during the Late Cretaceous by the ancestral Orange (the Karoo and Kalahari Rivers of de Wit 1999), which fed the thick depocentre of the Kudu delta and related deposits (Wickens & McLachlan 1990; Brown *et al*. 1995). This erosion preceding the major uplift and coastal incision recorded in the offshore at *c*. 65 Ma and was the result of widespread erosion of comparatively soft rock within the continent-scale (*c*. 1×10^6 km^2) Orange River drainage basin. The cover sediment is interpreted to comprise mostly sands, silts and clays, and is not considered to result from a marginal uplift, as postulated by Rust & Summerfield (1990).

Third, the postulated pre-Eocene and possibly Late Cretaceous uplift phase(s) of the entire Orange River drainage basin and, consequently, much of southern Africa, including the continental shelf south of Cape Cross (Holtar & Forsberg 2000; Aizawa *et al*. 2000), differs from previous views on the age of uplift. Partridge & Maud (2000) suggested a Pliocene uplift, based partly on east African data, and Burke (1996) interpreted the age of the uplift to be *c*. 30 Ma, based on the assumption that the earliest Cenozoic sediments on top of the folded Cretaceous strata are Oligocene in age. On the basis of apatite fission-track data, Brown *et al*. (1994) considered that by mid-Cretaceous times, 1–3 km of rock had been removed from the continent.

Fourth, the present-day, highly energetic coastal system, with sand moving onshore and gravel accumulating in the intertidal to subtidal zone, was established by Middle Eocene times at the latest. If the river mouth was also fixed, then the coastal energy was sufficient to move gravel some distance northwards along the shoreline. Between Late Cretaceous and Middle Eocene times there was a transition from a wave-dominated deltaic system to an extreme wave–aeolian-dominated system of sediment dispersal.

What caused the sediment dispersal system to change?

There is a combination of factors involved in this Late Cretaceous to Early Cenozoic change from a major phase of conventional delta building to a wave–aeolian-dominated coastal strip, the three principal ones being related to accommodation space (tectonics), climate and rate of sediment supply.

Accommodation space

From the initial major uplift phase recognized in the Late Cretaceous offshore southwestern Africa this inner shelf has remained remarkably buoyant throughout the Cenozoic (Siesser & Dingle 1981; Brown *et al*. 1995; Aizawa *et al*. 2000). Consequently, there has been comparatively little subsidence-induced accommodation space available on the inner shelf for retention of the sediments discharged from the Orange River during the 60–65 Ma since its post-Cretaceous incision. It is evident that this is an area of sediment bypass. Offshore mining and semi-submersible dives have shown that, in addition to the Eocene–Holocene sediment cover, there are numerous localized areas of bare basement outcrops in the inshore zone that are offlapped by successively younger Cretaceous successions (Kuhns 1995; Stevenson & McMillan 2004).

Climate and wind systems

The Namib Tract, which stretches for >2000 km from the Olifants River in South Africa to the Catumbela River in southern Angola, records several phases of aridity in the Cenozoic. The earliest phase is placed in the Middle Eocene, where aeolianites at Buntfeldschuh indicate active onshore sand dune movement under a dominant SW palaeo-wind (Ward & Corbett 1990) and evaporites in southern Angola testify to a dry climate (Soares de Carvalho 1961; Ward *et al*. 1983). The younger aeolian packages laid down under desert conditions with prevailing SW winds, notably the Tsondab Sandstone and its southern Namibian equivalents (Figs 2a and 4), have been dated biostratigraphically at Middle Miocene (16 Ma) to Late Miocene (10 Ma), although the ages of the base of these successions still remain unresolved and could date back to the Oligocene (Ward 1987; Pickford & Senut 1999). Post-Miocene aridity probably persisted through Pliocene to Recent times, as reflected in the Fiskus aeolianites that accumulated under strong SW airflow with the development of the contemporary main Namib Sand Sea (equivalent to the Sossus Sand Formation, SACS 1980; Ward *et al*. 1983), Skeleton Coast dune fields (Lancaster 2000) and Namaqualand dunes (Rogers 1977). Significantly, Hay & Brock (1992) suggested that the uplift of southern Africa restricted the airflow around the southeastern Atlantic High and intensified the summer low that develops over the Kalahari. This resulted in increased intensity of the wind system, which they considered to have happened during the Late Tertiary rather than the Late Cretaceous to Early Tertiary as is suggested here.

Sediment supply

The Cenozoic outfall from the incised Orange River was coarser grained, including medium cobbles derived from deep within the

Fig. 4. Photographs showing the Tsondab Sandstone Formation unconformably overlain by the Sossus Sand Formation, Namibia.

interior of southern Africa. The lack of accommodation space on the shelf during the Cenozoic precluded the build-out of a fluvial delta from the Orange River mouth. Consequently, fluvial outfall was fractionated in an energetic marine setting with unidirectional longshore drift driven by prevailing winds from the south-quadrant. The positions of the marine-to-land take-off points of the sand are thought to be controlled by three factors.

First, on a regional scale, the main Namib Sand Sea originates from, and is fed by, aeolian transport corridors situated in the northern Sperregerbeit in an area where the seismic sections demarcate the southern margin of the Lüderitz Arch (Aizawa *et al*. 2000; Fig. 2a). In this region, from just north of the present Orange River mouth there is a progressive attenuation of Aptian and post-Aptian sediments onto Mid- to Late Proterozoic basement. This persistent positive area would have promoted a build-up of the littoral sands transported northwards within the coastal strip, from there allowing the dominant onshore winds to move it inland.

Second, in the region between the Orange River mouth and Walvis Bay the orientation of the coastline swings from NW to a more northerly orientation, first at Chameis Bay and then again at Lüderitz (Fig. 2). These swings in orientation bring the coastline closer to the principal, south-quadrant, wind direction. At the same locations, there is a change in the nature of the bedrock. To the south, the bedrock of the Oranjemund sub-terrane is fairly constant in lithology, being mainly siliciclastic sedimentary rocks. At Chameis Bay, however, softer rocks begin to alternate with harder in a sequence of dominantly oceanic igneous rocks (Frimmel 2000*b*). This results in coastline retreat, realignment and the development of ‘J bays’, which initiate the sand transport corridors that are the conduits supplying the main Namib Sand Sea.

Third, gravel beaches disappear or are less significant in the Chameis region *c*. 120 km north of the Orange River mouth (Fig. 2b). Further south along the coastline, they may have been effective in occupying beach space so that there was little or no sand build-up for wind action to remove onto the land. Gravel beaches may also have been effective in trapping sand in inter-grain pore space at low tide only to have it return seaward during high tide.

In view of these three controls, which are all geographically constrained, it is likely that the sand take-off points fluctuated minimally in a north–south direction during the Cenozoic and remained relatively fixed areas over substantial time periods, thus allowing older aeolian formations to be preserved beneath younger dunefields (Figs 2 and 4).

Sediment distribution in the Tertiary: the effects of sea-level changes

Since the uplift and truncation of the Cretaceous sediments in the offshore, there have been wide fluctuations in sea levels, which, given the antiquity of the energetic coastline, would have had profound implications for the distribution of sediment over this period of time. Estimates for sea-level changes along this coast suggest a range from 170 m above present sea level in the Eocene to 120 m below present sea level in the late Pleistocene. During the Cenozoic interval there is also a world-wide, Oligocene sea-level lowstand, the effects of which are recognized elsewhere along the west African coast. Sea levels have also fluctuated significantly since the build-up of the Antarctic ice in the Eocene (Lear *et al*. 2000; Moran *et al*. 2006) through Pliocene and into Pleistocene to Recent times. With wave base at 30–80 m or even deeper according to the JAGO dives, a fall in sea level of 120 m could subject the present shelf to wave action down to depths of 150–200 m below current sea level.

It is difficult to estimate the area of shelf that may have been exposed to these processes since Eocene times. To judge from the disposition of known Eocene sediments in the offshore, there has been little significant post-Eocene regional change in elevation of the sea floor. The Cenozoic sediment cover is thin over much of the shelf offshore of the Orange River mouth and a little distance to the north, implying that there has been minor post-Late Cretaceous shallowing of this region by sediment accumulation. However, if the sediment discharged onto the shelf by the Orange River has now been displaced elsewhere, there would have been times when this sediment elevated the shelf floor and possibly also extended the width of that part of the shelf above wave base. By using present-day depth contours as a general (and possibly conservative) guide, it is possible that up to 150 km of the present shelf width would be above lowstand wave base (Fig. 5). The present coastal regime, with landward displacement of coarse sediment and a wider marine dispersal of

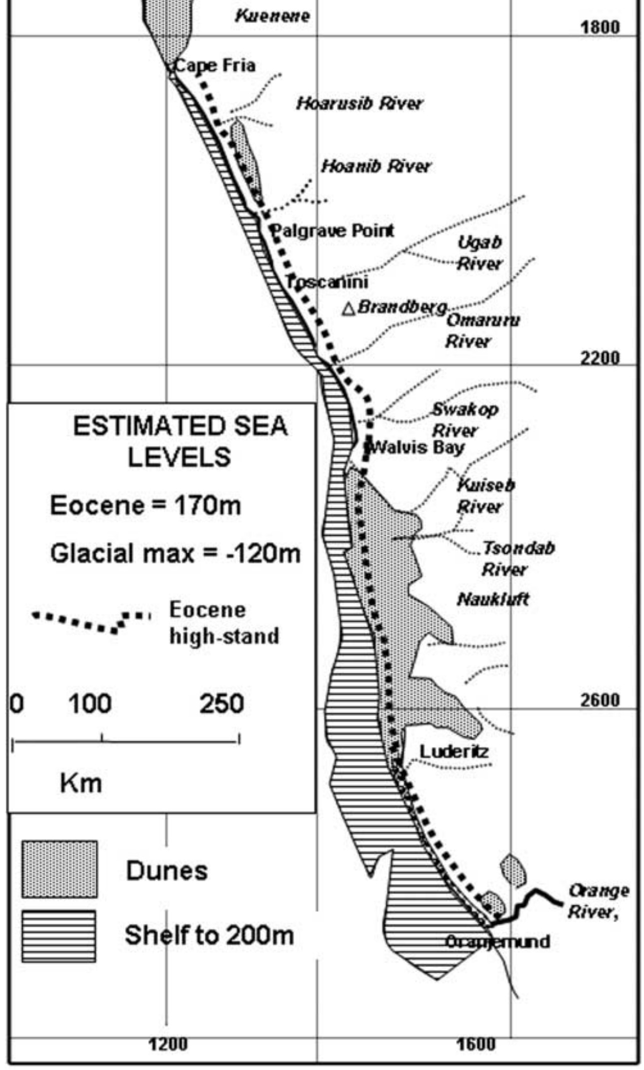

Fig. 5. Map showing variations in shelf extent between the Pleistocene glacial-maximum lowstand of sea level and the Eocene sea-level highstand.

fine material, has been in existence since at least the Middle Eocene. In Eocene and post-Eocene times the sediment discharged onto the shelf by the Orange River would have been subjected to roughly the same processes as those illustrated in Figure 2. During periods leading to lowstands, successive gravel beaches would have accreted to the shore near the contemporary Orange River mouth and *c.* 150 km (or greater) width of the shelf to the north would have been covered or partly covered by aeolian dune sands (Fig. 6a).

If the main Namib Sand Sea has been roughly the same size as now since the Eocene (Fig. 2a shows the distribution of the Tsondab Formation, which represents the older sand sheets), the distal edge of the palaeo-aeolian sand sheet would have lain within its present area. There may have been sand removal from the sand sea during times of diminishing sand supply. Apparent hiatuses in dune development there (Ward & Corbett 1990; Lancaster 2000; Fig. 4) may be the result of coastal regressions. Sea-level falls would have been accompanied by an increase in sediment discharge consequent on the rejuvenation of the river systems (Corbett 1993). Regression would also have caused reworking and displacement of the offshore mud belt either further offshore to the continental edge or further along the coast (Fig. 6b).

Subsequent periods of sea-level rise would have removed sediment in the same way as it does now. With the exception of the dunes tentatively described by Bagguley & Prosser (1999) as occurring on the present shelf, there appears to be little of the regressive dune sediment preserved at the end of each period of transgression (i.e. at sea-level highstands). It seems probable that all or most of the sand dunes accreted on the exposed former shelf had been transported incrementally landward during the transgression and there would have been, as a result, an increase in sand supply to the main Namib Sand Sea (Fig. 6b).

Classification of the Orange River dispersal system

The Orange River outfall and associated dispersal system is difficult to classify, because it does not fall easily into either the strandplain or delta category. The strandplain component is a stretch of gravel beaches a few kilometres wide and extending

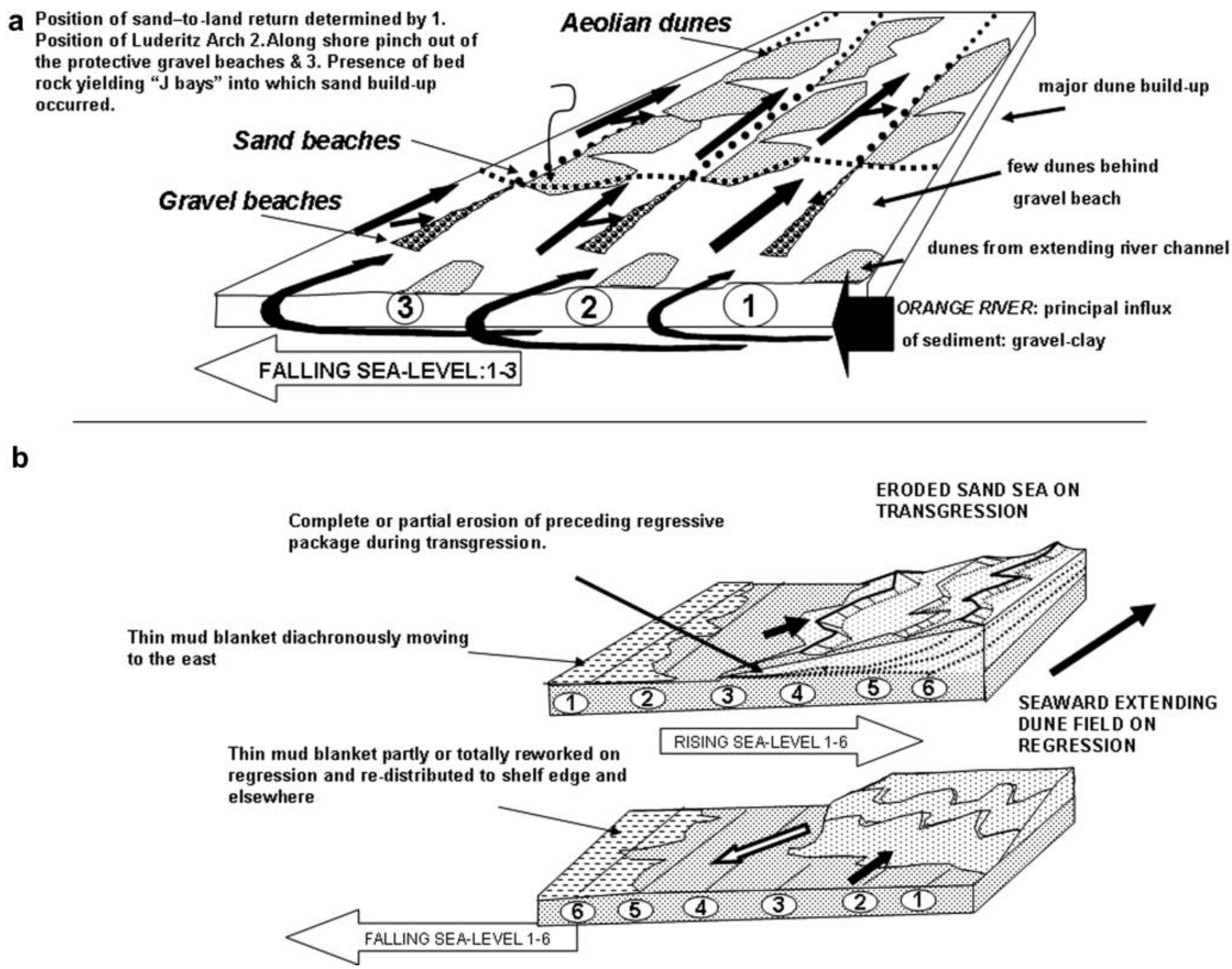

Fig. 6. Diagrammatic illustrations of the processes taking place in shelf areas subject to Tertiary reworking during sea-level changes. (**a**) Regression (during successive time steps 1–3) has yielded a sequence of gravel beaches and longshore-transported sand that has been displaced onto dune systems. (**b**) The behaviour of the dune field varies during regressions (lower scenario) and transgressions (upper scenario). (Numbers 1–6 refer to successive positions of the regressing or transgressing shoreline.)

for *c*. 120 km along the coast. For some distance, gravel is the only grain-size category capable of remaining at, and building up, the coastline in this energetic regime, and was maintained there in Plio-Pleistocene times by a massive delivery of gravel to the coast by the Orange River. The system is so energetic that all other sediment size fractions are widely dispersed either onto the land or much farther offshore.

The two recorded examples of wave-dominated deltas resembling the Orange River dispersal system are the Senegal and São Francisco. Here, the sediments accreting to the 'delta' are not principally sourced from the river around which the 'delta' has been constructed (Michel 1968; Dominguez 1996). Instead, these rivers act like a groyne intercepting sediment transported by wave-driven longshore drift. As pointed out by Dominguez (1996), the disassociation of the river from the deltaic sediment at its mouth seriously questions the application of the term 'delta' in these instances.

In the case of the Cenozoic Orange River deposits, variations in the composition of clast assemblages with time are recognized: siliceous, agate-bearing gravels typify the Middle Eocene, epidosite-rich gravels occur through much of the Miocene, and clasts of banded iron formation and Drakensberg basalt dominate the Plio-Pleistocene (Kaiser 1926; Fowler 1976; Van Wyk & Pienaar 1986). Resistant quartzite clasts derived from the Neocambrian Nama Group located within the Great Escarpment have also been prominent in the Orange River outfall since at least Miocene times. These gravels have been reworked into marine deposits, mainly beaches, in both offshore and onshore settings. Similarly, sands derived from the Orange River can be followed in an inshore zone running north of its mouth until the take-off points along the coast are encountered from where these sediments are blown on land for considerable distances to make up the Namib Sand Sea, as initially recognized by Rogers (1977). The heavy mineral assemblage of modern Namib dunes confirms an Orange River source (Lancaster & Ollier 1983). Although more difficult to fingerprint, the clays and silts offshore have been linked back to an Orange River source (Diester-Haas *et al*. 1988; Holtar & Forsberg 2000).

Thus, in the case of the Orange River, the dispersed sediment is clearly derived from the river outfall, in a manner more direct than in some examples of wave-dominated deltas. There is a transition from a clearly defined Cretaceous delta to the unusual, present-day coastal accretionary belt. Coleman (1981) defined a delta as 'those coastal deposits, both subaqueous and subaerial derived from river-borne sediments'. If this definition is accepted, then, however bizarre it may seem, the widely dispersed sediments, including the clays of the shelf edge and sands of the main Namib Sand Sea, can be regarded as being the component parts of a single delta. Within this definition, the Orange River delta is an extreme case of a delta dominated by combined wave and wind processes (Fig. 7).

Conclusions

The southern Namibian shelf, one of the most energetic environments in the world, has been a sediment bypass area since the end of the Cretaceous to early Cenozoic time, when a widespread epeirogenic uplift affected much of southern Africa, including the continental shelf. During this time interval, a vigorous, oblique-to-coast wave system with attendant unidirectional, northward longshore drift driven by strong SW winds evolved, and later a number of coastal and deeper currents developed. These currents have collectively dispersed sediment over a great area of the eastern South Atlantic sea floor and associated continental margin.

The uplift resulted in a lack of accommodation space in the region offshore of the Orange River mouth, which in conjunction with the coeval development of a highly energetic coastal system, resulted in the splitting of the delivered sediment load into various size fractions each with separate dispersal paths. In the present and recent past, gravel has accumulated along a coastal strip that extends for *c*. 120 km northwards from the

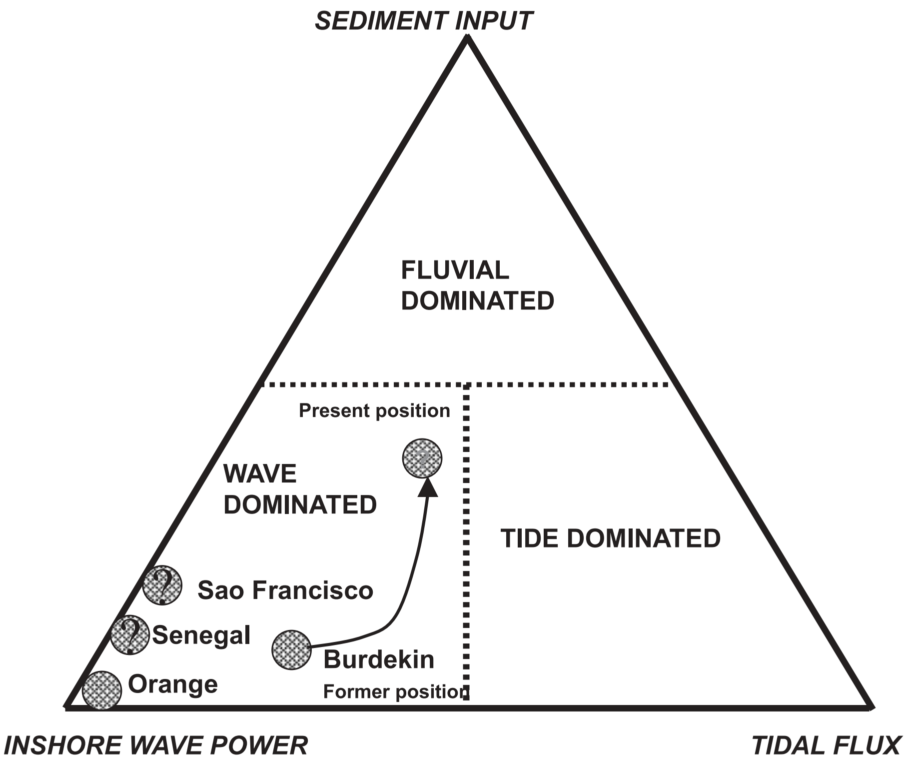

Fig. 7. Summary diagram of the Orange River in the scheme of deltas.

mouth of the Orange River; sand, predominantly transported along the shoreface and beach, fed the dunes of the main Namib Sand Sea; mud, being more mobile, extended over the shelf to partly build up the shelf edge and extend the northern margin of the shallow inner shelf.

During this time, with the operation of extreme wave energy and a consequent longshore drift system, the shallow shelf has been combed by repeated regressions and transgressions, driven by relative sea-level fluctuations. This mechanism has extensively reworked sediment supplied by the Orange River onto the shelf, which is considered an area of net sediment bypass. The bulk of the sand and mud has been removed by intense wave activity. Gravel, originally emplaced on the shelf in regressive beaches, has remained as relatively condensed sediment units overlying the reworked surface.

The area of vigorous sediment reworking is estimated at *c*. 22 500 km^2, excluding a substantial area of the present land surface known to have been flooded during sea-level highstands. Older sediments dating back to at least the Middle Miocene and that include beach gravel, shoreface gravel and sands, and aeolian dune sands are evidence of the antiquity of this dynamic shore system.

The Orange River had essentially incised into bedrock (local basement) after the generation of a Late Cretaceous delta but before the early Miocene, the age of the earliest dated terrace deposits along the incised river (*c*. 19 Ma; Pickford *et al*. 1996). The coastal system was supplied with a sediment volume at least equal to the combined volume of: (1) material eroded from the Richtersveld sector of the Great Escarpment by the middle Orange River; (2) sediment yielded from the incision on the Upper Orange River; (3) the Cretaceous sediment reworked from the shelf.

The classification of this dispersal system is difficult. Although it compares with small gravel-dominated fan-deltas, often found in pro-glacial regions, and with some smaller wave-dominated deltas where onshore wind systems return sediment to the land, it is unique in its scale, vigorous and continual energy, diverse shelf currents and antiquity. It has evolved from a well-recognized Late Cretaceous deltaic complex. By reworking of the older deltas and by a new sediment contribution from post-uplift rejuvenation of rivers, it is fairly clear that the bulk of the sediment in the delta belongs to the evolving Orange River drainage system. Other than the extreme dispersal of the sediment and the consequent lack of a major topographical feature at its immediate mouth, there seems every reason to classify it as a delta, albeit a highly unusual one dominated by combined wave and wind processes.

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