Ultra-long distance littoral transport of Orange sand and provenance of the Skeleton Coast Erg (Namibia)

Article *in* Marine Geology · November 2014

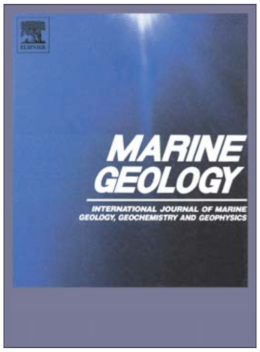
DOI: 10.1016/j.margeo.2014.07.005

Eduardo Garzanti
Università degli Studi di Milano-Bicocca

Sergio Andò
Università degli Studi di Milano-Bicocca

Marta Padoan
Università degli Studi di Milano-Bicocca

Giovanni Vezzoli
Università degli Studi di Milano-Bicocca



Ultra-long distance littoral transport of Orange sand and provenance of the Skeleton Coast Erg (Namibia)

Eduardo Garzanti, Pieter Vermeesch, Sergio Andò, Michele Lustrino, Marta Padoan, Giovanni Vezzoli

PII: S0025-3227(14)00213-8
DOI: doi: 10.1016/j.margeo.2014.07.005
Reference: MARGO 5141

To appear in: *Marine Geology*

Received date: 27 December 2013
Revised date: 9 July 2014
Accepted date: 23 July 2014

Please cite this article as: Garzanti, Eduardo, Vermeesch, Pieter, Andò, Sergio, Lustrino, Michele, Padoan, Marta, Vezzoli, Giovanni, Ultra-long distance littoral transport of Orange sand and provenance of the Skeleton Coast Erg (Namibia), *Marine Geology* (2014), doi: 10.1016/j.margeo.2014.07.005

Ultra-long distance littoral transport of Orange sand and provenance of the Skeleton Coast Erg (Namibia)

Eduardo Garzanti[1]*, Pieter Vermeesch[2], Sergio Andò[1],
Michele Lustrino[3], Marta Padoan[1], Giovanni Vezzoli[1]

[1] *Laboratory for Provenance Studies, Department of Earth and Environmental Sciences, Università di Milano-Bicocca, 20126 Milano, Italy*

[2] *University College London, London WC1E 6BT, UK*

[3] *Dipartimento di Scienze della Terra and Istituto di Geologia Ambientale e Geoingegneria (IGAG) - CNR, Università degli Studi di Roma La Sapienza, 00185 Roma, Italy*

* Corresponding author. Tel.: +39-02-64482088

E-mail addresses: eduardo.garzanti@unimib.it (E. Garzanti), p.vermeesch@ucl.ac.uk (P.Vermeesch), sergio.ando@unimib.it (S. Andò), michele.lustrino@uniroma1.it (M.Lustrino), marta.padoan@unimib.it (M. Padoan), giovanni.vezzoli@unimib.it (G. Vezzoli)

[1] Tel.: +39-02-64482088; fax: +39-02-64482073.
[2] Tel.: +44-020-76792418; fax: +44-020-76792867
[3] Tel.: +39-06-49914158; fax: +39-06-4454729

Key words: Namibian deserts; Orange River; Diamond placers; Sedimentary petrology; Pyroxene, garnet, staurolite chemistry; Detrital zircon geochronology.

ABSTRACT

Quantitative provenance analysis based on high-resolution bulk-petrography and heavy-mineral data on beach and dune sands, integrated with detrital-zircon geochronology and chemical analyses of pyroxene, garnet and staurolite, demonstrates that sand derived from the Orange River is carried by powerful and persistent longshore currents as far as northern Namibia and southern Angola, 1750 km north of its mouth. This is the longest cell of littoral sand transport documented so far. Compositional forward modeling indicates that ≥ 80% of dune sand in the Skeleton Coast is Orange-derived, the remaining ≤ 20% being supplied by slow erosion of the Damara Orogen chiefly via the Swakop River. A decrease in basaltic rock fragments and pyroxene with relative enrichment in garnet, staurolite, tourmaline and other metamorphic minerals north of Walvis Bay indicates that only one-third of beach sand in the 350 km dune-free gap between the Namib and Skeleton Coast Ergs is Orange-derived, the remaining two-thirds being supplied largely by the Swakop River draining the Damara Orogen. Although volcanic gravel becomes dominant in beaches of the Skeleton Coast north of the Uniab mouth, detritus from Cretaceous Etendeka lavas accounts for only 4% of beach sand, reflecting limited sand generation in the arid catchment. Contributions from the Kunene River to either dune or beach sands is ruled out, indicating that gem diamonds found in placer deposits along the coast of Namibia are all derived from the Orange River.

1. Introduction

Coastal Namibia is a very special hyperarid setting characterized by net northward sand transport under the action of powerful longshore currents. Because of the extreme climatic conditions chemical weathering is negligible, and changes in sediment composition produced exclusively by physical processes can be monitored during multistep transport in high-energy environments over distances of many hundreds of kilometers. This study combines high-resolution bulk-petrography and heavy-mineral data with detrital-zircon geochronology and chemical analyses of pyroxene, garnet and staurolite grains to define the compositional trends observed along the coast of Namibia, to identify distinct sediment sources, and to quantify their relative contributions to beaches and dune fields. In particular, we will assess provenance of sand in the Skeleton Coast Erg (Fig. 1), determine supply from hinterland rivers draining different branches of the Damara Orogen or Etendeka lavas, and specifically evaluate the extent of northward transport from the Orange mouth and the possibility of southward transport from the Kunene mouth, which has notable economic implications in the search for diamond placers.

2. Coastal Namibia

The 1570 km-long coast of Namibia faces the Atlantic Ocean between the mouths of the Orange and Kunene Rivers. The narrow coastal plain is delimited by the escarpment, a pronounced rise in topography which encircles the whole of southern Africa and delimits a mountainous hinterland at elevations between 1000 and 2000 m. The Lower Cretaceous Brandberg granite (Schmitt et al., 2000) rises to 2574 m. Topography was built initially during Early Cretaceous rifting of the southern Atlantic, associated with flood-basalt eruptions and domal uplift. Subsequent rejuvenation took place in the Late Cretaceous (Guillocheau et al., 2012), whereas river canyons have been deeply incised during a late Pliocene event of accelerated denudation (Ward, 1987; Van der Wateren and Dunai, 2001). Fission-track and cosmogenic-nuclide data indicate low erosion rates throughout coastal Namibia, where landscapes have been changing slowly since the Miocene (Cockburn et al., 2000; Bierman and Caffee, 2001).

2.1 Arid climate

Arid climates in coastal Namibia were established since the Miocene, when the effect of the quasi-stationary southern Atlantic anticyclonic system on the southwestern rain-shadow side of southern Africa was reinforced by expansion of the Antarctic ice sheet and installation of the Benguela upwelling system (Fig. 1; van Zinderen Bakker and Mercer, 1986; Rogers and Bremner, 1991; Compton et al., 2004). Upwelling of Antarctic water offshore causes low sea-surface temperatures, low humidity of southerly winds and very little rain through the year, but frequent fogs. Annual precipitation increases from < 50 mm near the coast and ~ 100 mm at the foot of the escarpment to 300-500 mm on the plateau and mountain area, where rain falls mainly during summer (Heine, 2005). Strong onshore southerly to southwesterly winds dominate the coastal regime all year round, moving sand for ~ 50% of the time and accounting for 98% of the sand flux along the Skeleton Coast (maximum in August to October), where they reach speeds of 31 m/s (Lancaster, 1982). Also significant are monsoonal influences from the northeast, associated with disturbances of the Intertropical Convergence Zone. Easterly *bergwinds* are common in winter, and responsible for 15-20% of potential sand flux in the Namib Erg (Lancaster, 1985). *Bergwinds* blow between April and July along the Skeleton Coast, where they reach speeds of 17 m/s and play a role in sediment transport, with dust plumes extending ≥ 100 km offshore (Krapf et al., 2005).

The cold surface layer of the Benguela current, ≤ 50 m thick adjacent to the coast, drifts equatorward with an average speed of ≤ 8 cm/s to converge with the warm, poleward Angola Current between 14°S and 16°S. The underlying nutrient-rich South Atlantic Central Water, playing a key role in Benguela upwelling, is characterized instead by poleward time-averaged flow, with average speed of ≤ 6 cm/s. This undercurrent exists all along the SW Atlantic coast, and may breach to the surface at times of reduced southerly wind-stress. At greater depths, Antarctic Intermediate Water also moves poleward along the Namibia coast (Compton et al., 2008).

2.2 Coastal deserts

Coastal Namibia hosts three separate dune fields. The major one is the Namib (~ 34,000 km^2), stretching along the coast between Lüderitz and the Kuiseb River, and for 100-150 km inland to the base of the escarpment at the 1000 m contour. The Namib Erg is dominated by large linear dunes, with a belt of simple and compound transverse and barchanoid dunes along the coast and areas of star-shaped dunes on its eastern margin (Lancaster, 1989). Locally exposed in interdune areas is the partially lithified Tsondab Sandstone, representing a Miocene analogue of the modern dune system (Kocurek et al., 1999). North of Walvis Bay, the coast of the Erongo region is a rocky plain with low ranges of hills and *inselbergs* where metamorphic, granitoid, and finally volcanic rocks are exposed, in a ~ 350 km wide dune-free gap. Farther north, the Skeleton Coast Erg (~ 2,000 km^2) runs 2-5 km inland parallel to the coast for 165 km between south of Torra Bay and the Hoarusib River. Schists, granites or basalts are exposed in coastal areas, where diamond-bearing raised beaches occur at Toscanini and Terrace Bay (Moore and Moore, 2004). Barchanoid dunes superimposed on the coastal deflation surface dominate in the south, whereas ≤ 50 m high compound transverse dunes occur in the north. The width of the dune belt widens discontinuously northward from 6 to 22 km. Simple barchan dunes 3-10 m high occur along the eastern downwind margin of the erg. Instead, larger dunes are developed along the western windward edge of the erg, where sand supply is greater, and in places coalesce to form a longitudinal dune wall ≤ 80 m high with a large slip face to the east. Sand is fine to medium-grained throughout the erg, with frosting and reddening increasing landward (Lancaster, 1982). A third dune field, starting with barchan trains and linear sand streaks north of Cape Fria, straddles the mouth of the Kunene River and extends northwards to the Moçâmedes Desert of southern Angola.

2.3 Ephemeral rivers

All rivers between the Orange and the Kunene are ephemeral. Summer thunderstorms and torrential rainfall in the mountainous hinterland may generate high-magnitude floods that last several days, but otherwise they may experience several years of drought. Rivers represent a significant source of coastal sand only in the Erongo region, where their route to the Atlantic Ocean is not barred by dune fields. The Ugab is the largest, with a catchment area of 29,360 km^2, a length approaching 500 km and an annual runoff of 20 10^6 m^3, followed by the Swakop (21,010 km^2), Kuiseb (16,690 km^2), Huab (16,470 km^2) and Omaruru (11,580 km^2; Strohbach, 2008). Flows in the Uniab (110 km, 3960 km^2) and Koigab (130 km, 2320 km^2) are infrequent and short, because only 2% of the catchment receives > 100 mm of annual rain. The larger Hoanib (270 km; 15,760 km^2) and Hoarusib (300 km; 15,240 km^2) farther north receive higher rainfall because of proximity to the intertropical convergence zone. Flows are more frequent, and exceptional events cause repeated floods with higher discharge. The Hoarusib River reaches the ocean almost every year, and supports large wetlands and a riparian forest along its banks (Jacobson et al., 1995).

2.4 Competing fluvial and eolian processes

Rivers draining the escarpment east of the Namib Erg cannot reach the ocean, and penetrate ≤ 50 km into the desert to empty their waters in flat interdune playas. Fluvial sediments are a negligible source for the dunes, whereas wind-blown sand readily accumulates on the river bed, and finally chokes fluvial transport. The Kuiseb River, flowing along the northern edge of the Namib and occasionally reaching the ocean (16 times since 1837; Morin et al., 2009), does provide sand to the dunes but only locally, and fluvial bedload progressively mixes with eolian sand downstream. Rivers of the Skeleton Coast reach the ocean only during major floods (6 times in 63 years; Jacobson et al., 1995). In the south, where the most effective barrier to water flow is the western dunewall, rivers are dammed within the erg. In the north, where the dune belt is higher and wider, rivers are dammed more effectively, and flood basins form east of the erg (Krapf et al., 2003). Only the Koigab River freely reaches the ocean, delivering gravel derived from Etendeka lavas. Isolated trains of barchans form across the fan deflation surface and move to join the erg ~ 15 km to the north. The contribution of wind-blown sand from the coast to river deposits was calculated to increase from 5% at the fan apex to 50% in the distal fan, based on heavy-mineral and grain-size data (Krapf et al., 2005). The Uniab River cuts across the ~ 7 km wide southern tip of the Skeleton Coast Erg, where < 20 m high dunes do not represent an unsurpassable barrier. Because of the high yield strength of smectite-rich sediment-water mixtures, hyper-concentrated flood flows generated by catastrophic breakthrough and dune collapse may carry outsized boulders up to 5 m in diameter. Healing of the dune belt requires considerable time after floods, and the river bed is easily traced through the erg even after many years of drought (Svendsen et al., 2003). The Hoanib River is efficiently blocked by the northern dune belt to form a large flood basin east of the erg. During exceptional rainfalls, flood waters build up for days, until they overtop a low point of the dune barrier. Interdune trends then guide the river through the erg, and provide access for lateral flooding into interdune areas. In the aftermath of floods, fluvial bars are rapidly deflated and dunes migrate up channel to cover the river bed with low bedforms in a few weeks. Complete healing of the dune belt takes considerable time, because successive floods may repeatedly flush the river passage once the initial barrier to their entry into the erg has been breached (Stanistreet and Stollhofen, 2002). Although wind-blown sand mostly moves northward, broadly perpendicular to fluvial transport, funnelling by deeply incised valleys such as those of the Hoanib and Hoarusib Rivers induces eastward eolian transport and deposition of low dunes as far as 50 km upstream of the main erg.

Eolian processes, however, do not invariably prevail on fluvial processes. Floods in the incised Kuiseb and Hoarusib valleys are sufficiently frequent to flush eolian sand, and thus terminate dune migration at the northern edge of the Namib and Skeleton Coast Ergs (Ward, 1987). Dunes of the Coastal Namib cross the Kuiseb valley near Walvis Bay, but are finally stopped by the Swakop River. Northward advance of Skeleton Coast dunes is similarly interrupted by the Hoarusib River. Near the coast only, where the valley is less incised and floods less frequent, a 1-2 km wide train of barchans continues for 25 km to the Khumib River. The Kunene Erg is arrested in much the same way by the perennial Kunene River (Hartmann and Brunotte, 2008), but northward eolian sand transport continues in the Moçâmedes Desert and finally comes to an end at the incised Curoca River valley in southern Angola (Lancaster, 1982).

2.5 Sediment transport

The Orange River has remained the most prominent sediment source to coastal Namibia throughout the Neogene (Rogers, 1977). Sand and gravel delivered at the mouth are pushed northward by a powerful longshore drift under dominant southerly winds, whereas mud is largely carried offshore (Rogers and Rau, 2006). Wave base is ~ 100 m deep, and the whole inner shelf is subject to intense sediment transport during storms. Very coarse sand to medium pebbles are entrained to depths of 30 m, and cobbles to 15 m (Bluck et al., 2007). Much of the sand, retained within the breaker zone and moving northward in a ≤ 3 km wide belt (Spaggiari et al., 2006), bypasses the Sperrgebiet deflation area and accumulates in the Namib Erg, while offshore sand transport continues to beyond Walvis Bay (Corbett, 1993). Biogenic carbonate grains represent only a minor fraction of sand in beaches and dunes of coastal Namibia (mostly ≤ 1%). Eustatically-controlled sand cycling from the littoral to the eolian environment and back has occurred repeatedly in the recent past. Drowned coastal dunes and beach ridges emplaced during Pleistocene lowstands are believed to underlie most of the inner shelf, where upwelling has led to deposition of organic-rich diatomaceous muds, with phosphorite deposits and influx of eolian detritus from the land. Calcareous foraminiferal oozes dominate offshore. Terrigenous deposits blanket most of the shelf close to the Kunene mouth, where glauconite occurs (Bremner and Willis,1993).

Oceanic circulation influences the distribution of clay in a more complex way. Poleward-directed tongues of the Angola-Benguela Front, formed at times of reduced southerly-wind stress, entrain smectite and kaolinite supplied by the Kunene, which eventually settle in a narrow mudbelt extending 90 km south of the river mouth. Clays travelling past the narrow shelf are carried much farther south by Antarctic Intermediate Water along the upper slope. Similarly, a mudbelt extends ~ 600 km south of the Orange mouth under the effect of poleward undercurrents (Compton et al., 2010). Dominant illite offshore the Namib Erg and Erongo coast indicates eolian input by bergwinds (Bremner and Willis, 1993).

2.6 Geology of Namibia

Namibia is crossed by the Mesoproterozoic Namaqua and Neoproterozoic Damara Orogens, welding the Archean Kalahari and Congo Cratons (Fig. 1; Jacobs et al., 2008). The Namaqua belt of southern Namibia includes Paleoproterozoic basement and medium/high-grade metasediments interpreted as originally deposited on a passive margin (Becker et al., 2006). Exposed east of the Namib Erg is the Mesoproterozoic Sinclair Group, largely overprinted by Damaran structures in the Rehoboth area. These volcanic and subordinate sedimentary rocks rest disconformably on metasedimentary and metavolcanic rocks intruded by 1.37 Ga tonalite, and have been interpreted to represent either a rift zone (Borg, 1988) or the active margin of the Kalahari Craton facing an eastdirected subduction zone (Hoal, 1993). Widespread intrusion of granitoid batholiths was followed by outpouring of continental tholeiites at ~ 1.1 Ga.

The Neoproterozoic to Cambrian Damara Orogen, including 2.0-1.2 Ga polymetamorphic gneisses and overlying metasediments intruded by 570-460 Ma granites, has triple-junction geometry (Fig. 1; Miller, 2008). The Gariep Belt, the southern coastal arm, consists of Neoproterozoic successions locally hosting volcanic rocks and overprinted by up to lower amphibolite-facies metamorphism (Frimmel and Frank, 1998). The Kaoko Belt, the northern coastal arm, is the eroded core of a sinistral transpressional orogen (Goscombe et al., 2003a). In the middle, the Inland Branch trends ENE–ward into Botswana, connecting to the Pan-African orogenic system via the Zambezi and Mozambique Belts (Martin and Porada, 1977). In the Southern Zone of the Inland Branch, which lacks granitoid intrusions, metamorphism increases northward from greenschist to amphibolite facies. Granulite facies and partial melting were reached around ~ 510 Ma in the Central Zone along the coast (Longridge et al., 2011). The Northern Zone comprises greenschist-facies carbonate to siliciclastic metasediments and Proterozoic basement (Huab Gneiss). Greenschist-facies Neoproterozoic turbidites including granitoid intrusions represent the southern tip of the Kaoko Belt south of the Etendeka plateau (Ugab Zone; Goscombe et al., 2003a). The Eastern Kaoko Zone, representing the foreland, includes Paleoproterozoic metamorphic rocks and granitoids (Kamanjab basement) and the very low-grade Otavi carbonates. Metamorphism increases westward to upper-amphibolite facies in the east-vergent basement-cored nappes of the Central Kaoko Zone. Granulite facies and partial melting were reached in the Western Kaoko Zone at 580-570 Ma, followed by low-grade retrogression (Goscombe et al., 2003b). Along the coast, an arc terrane comprises upper-amphibolite facies metapsammites and metagranitoids (Gray et al., 2008). In the north, the Kunene Zone includes Neoarchean to Mesoproterozoic gneissic basement (Epupa Complex) regarded as the southwestern margin of the Congo Craton, the Kunene Intrusive Complex dated at 1.37 Ga and representing one of the largest anorthosite bodies on Earth, and low-grade Neoproterozoic metasediments (Becker et al., 2006).

In southern Namibia, Mesoproterozoic basement is overlain by 3 km-thick, shallow-marine to fluvial Neoproterozoic/Cambrian sandstones, mudrocks, and limestones deposited in the foreland basin of the Damara Orogen (Nama Group; Blanco et al., 2011). Deformation increases northward in very-low-grade slates and phyllites of the Naukluft mountains (Ahrendt et al., 1978). Carboniferous to Lower Jurassic Karoo terrigenous sediments and basalts are exposed in the east. The Etendeka lavas of western Namibia, generated during rifting of the southern Atlantic at ~ 132 Ma, overlie Lower Cretaceous eolian sandstones, Permian Karoo sediments or Damara basement, and consist of ~ 1 km thick, largely flat-lying basalts with quartz-latites at higher levels (Ewart et al., 2004). Tholeiitic sills and intrusive gabbros, diorites, granites and syenites occur in the Huab and Ugab catchments in the south (Jerram et al., 1999). Etendeka lavas are also exposed along the coast from south of Terrace Bay to the intersection with the Walvis Ridge.

3. Sampling and analytical methods

To investigate compositional trends along the coast of Namibia and quantify provenance of Skeleton Coast dunes, we have collected 42 sand samples from eolian dunes, beaches and river beds from south of Lüderitz to Möwe Bay in September-October 2011. Also considered in this study are 12 additional sand samples from the Namib Erg, 1 from the Moçâmedes Desert, and 35 from other rivers draining into the Atlantic, including the Orange and Kunene. We have sampled fluvial megaripples wherever possible to minimize contamination by wind-blown sand on dry river beds, and invariably the crest of largest dunes and beaches away from patches of deep-pink or black sand to avoid anomalous enrichment in heavy minerals.

Bulk sand was impregnated with araldite, cut into thin sections, and analysed by counting 400 points under the microscope (Gazzi–Dickinson method; Ingersoll et al., 1984). Average rank of metamorphic rock fragments was expressed by the Metamorphic Indices MI or MI*, ranging respectively from 0 (detritus from sedimentary and volcanic rocks) or 100 (detritus from very low-grade metamorphic rocks) to 500 (detritus from high-grade metamorphic rocks; Garzanti and Vezzoli, 2003). Sands are classified according to their main components exceeding 10%QFL (e.g., in a litho-feldspatho-quartzose sand Q > F > L > 10%QFL).

Heavy-mineral analyses were carried out on a quartered aliquot of the bulk sample, or mostly of the 32-500 μm class obtained by dry-sieving for poorly-sorted river samples. Heavy minerals were separated by centrifuging in sodium polytungstate (density ~ 2.90 g/cm^3), and recovered by partial freezing with liquid nitrogen. On grain mounts, 200-250 transparent heavy-mineral grains were either counted by the area method or point-counted at suitable regular spacing under the microscope to obtain real volume percentages (Galehouse, 1971). Dubious grains were checked by Raman spectroscopy. Heavy-mineral concentration was calculated as the volume percentage of total (HMC) and transparent (tHMC) heavy minerals (Garzanti and Andò, 2007). Heavy-mineral suites range from "very poor" ($0.1 \leq HMC < 0.5$) and "poor" ($0.5 \leq HMC < 1$), to "rich" ($5 \leq HMC < 10$), "very-rich" ($10 \leq HMC < 20$) and "extremely rich" ($HMC \geq 20$). To identify provenance of pyroxene, garnet and staurolite grains, mineral separates from samples of 10 Namib Erg, Skeleton Coast Erg, and Orange, Swakop and Koigab River sands were mounted with epoxy resin and analyzed with full WDS procedure using a Cameca SX-50 microprobe at the CNR-IGAG laboratories (method illustrated in Lustrino et al., 2005).

To trace sediment transport and provenance of the Skeleton Coast Erg, the U–Pb ages of 100 to 140 zircon grains were determined for each of three dune samples collected along the western dunewall near Torra Bay, Terrace Bay and Mőwe Bay, for Orange River sand, and for Namib Erg dunes. Analyses were made at the London Geochronology Centre using Agilent 7500 and 7700 LA-ICP-MS systems, employing a New Wave 213 nm frequency-quintupled Nd-YAG laser operated at 10 Hz with a 40 μm spot size and ~ 8 J/cm^2 fluence. To treat all samples equally and avoid intersample bias, the laser spot was always placed in the middle of zircon grains. We used ^{206}Pb/^{238}Pb and ^{207}Pb/^{206}Pb ages for zircons younger and older than 1100 Ma, respectively. Grains with > 10% age discordance were discarded. No common Pb correction was applied. The complete petrographic, mineralogical, geochemical and geochronological datasets are provided in Appendix A.

4. Sand composition

4.1 Orange River and Coastal Namib

The Orange catchment includes ~ 10^6 km^2 in southern Africa, where source rocks range from Archean and Paleoproterozoic basements exposed north of its Vaal tributary to the Carboniferous-Lower Jurassic Karoo siliciclastics capped by flood basalts in Lesotho. Orange sand is feldspatho-litho-quartzose to litho-feldspatho-quartzose, with plagioclase > K-feldspar and equally abundant mafic volcanic/subvolcanic and sedimentary (shale/sandstone, carbonate) rock fragments. Heavy-mineral assemblages are rich and clinopyroxene-dominated, with subordinate opaque Fe–Ti–Cr oxides, epidote, amphibole and garnet. The remarkably homogeneous clinopyroxene composition, with dominant Ti-poor and commonly Cr-rich and Al-rich augites plus subordinate pigeonites, indicates provenance from Karoo basalts (Garzanti et al., 2012a). U/Pb zircon ages are characterized by prominent Damara and Namaqua peaks at ~ 0.6 and ~ 1.0 Ga, with a few older grains clustering at 1.8-2.1 Ga and younger grains at ~ 0.3 Ga (Vermeesch et al., 2010). Dune and beach sands of the Coastal Namib Erg are feldspatho-quartzose with common basaltic grains and rich clinopyroxene-dominated suites including garnet, amphibole and epidote (Fig. 2A). Detrital garnet is mostly almandine with subordinate pyrope molecule; almandine-spessartine, almandine-grossular or spessartine-almandine solid solutions also occur. Detrital modes, clinopyroxene chemistry and zircon-age spectra are the same as in Orange sand.

4.2 Rivers north of the Namib

Fluvial sands derived from the Damara Orogen range from metamorphiclastic to plutoniclastic. The Kuiseb River drains quartzites and micaschists above the staurolite and kyanite isograds (Hartmann et al., 1983; Jung and Mezger, 2003), and carries quartzose to feldspatho-quartzose sand with abundant biotite and a moderately-rich amphibole-epidote-garnet suite including apatite and tourmaline (Fig. 3). The Swakop River drains granites and metasedimentary rocks straddling the sillimanite isograd, and carries feldspatho-quartzose sand with common biotite and a moderately-rich amphibole-garnet-staurolite suite including clinopyroxene, tourmaline, apatite, titanite, and minor kyanite and sillimanite (Fig. 2B). Pyroxenes are mainly augite, Cr-rich augite, Al-rich augite and pigeonite as in Coastal Namib dunes, indicating mixing with eolian sand in the coastal plain. Diopside derived from upper-amphibolite-facies Damara metasediments exposed in the catchment (Puhan, 1983) also occurs (Fig. 4). Garnets are mainly almandine-pyrope and almandine-spessartine solid solutions, with minor almandine-grossular (Fig. 5). Staurolite grains have FeO/MgO ratios of 7.1±0.6 and moderate ZnO (0.4±0.1wt%).

The Omaruru River drains the high-grade core of the Damara Inland Branch where granites are exposed widely, and carries feldspatho-quartzose sand rich in feldspars and granitoid rock fragments, with a moderately-poor tourmaline-garnet-amphibole-epidote-titanite suite including fibrolitic and subordinately prismatic sillimanite. The Ugab River, draining the northern Inland Branch and the Brandberg granite, also carries quartzo-feldspathic sand. In the lower tract cutting across the Ugab Zone, low/medium-rank metapsammite and carbonate rock fragments increase, and the moderately-poor clinopyroxene > hornblende > garnet > epidote suite is enriched in zircon and tourmaline. The Huab River drains the Kamanjab basement, flows along the southern edge of the Etendeka plateau, and carries at the mouth basaltic pebbles mixed with litho-feldspatho-quartzose sand wind-blown from the coast. The moderately rich clinopyroxene > hornblende > garnet > epidote suite includes hypersthene and olivine. The Koigab and Uniab Rivers drain the Etendeka plateau (Fig. 2C), and carry feldspatho-lithic sand with mafic volcanic to hypabyssal rock fragments, subordinate plagioclase and virtually no quartz in the upper course, where rich to very rich clinopyroxene-dominated suites include Ti-poor to Ti-rich magnetite and ilmenite. Clinopyroxenes are dominantly augite with a few pigeonites, and tend to be richer in Na, Ti, Mn, Fe and poorer in Mg, Ca, Cr and Si than in Orange and Coastal Namib sands (Fig. 4). Farther north, the Hoarusib River drains the Kaoko Belt, and carries feldspatho-quartzose sand with plutonic and very-low to high rank metasedimentary rock fragments; moderately-rich, epidote-dominated suites include amphibole and minor garnet. Litho-feldspatho-quartzose sand of the Hoanib River is similar, but includes mafic volcanic rock fragments, plagioclase and clinopyroxene from Etendeka lavas.

4.3 Beaches and dunes north of the Namib

In the Erongo region north of Walvis Bay, beach sands record a decrease in basaltic grains and the appearance of micas and very-high rank metasedimentary rock fragments including metacarbonate (Fig. 2D). Staurolite, garnet, hornblende and tourmaline notably increase at the expense of clinopyroxene. Sillimanite, kyanite, andalusite, apatite and titanite occur more frequently. Volcanic rock fragments increase again in the Skeleton Coast north of Torra Bay (Fig. 2E), reaching 10% and

20% of bulk sand in gravel-dominated pocket beaches at Terrace Bay and Möwe Bay. Clinopyroxene tends to slightly increase north of the Huab mouth.

Dune sand in the Skeleton Coast Erg is feldspatho-quartzose to litho-feldspatho-quartzose, with rich clinopyroxene-dominated heavy-mineral suites as Coastal Namib sand but with less volcanic rock fragments, less pyroxene, and more staurolite, garnet, tourmaline and amphibole (Fig. 2F). Detrital clinopyroxenes are Ti-poor and commonly Cr-rich or Al-Cr-rich augite, with frequent pigeonite as in Orange River and Coastal Namib sands. A few diopside grains probably derived from Damara metasediments also occur (Fig. 4). Most augite grains are poorer in Ti and have lower Mg# than those in Upper Koigab sand, suggesting that very few were derived from Etendeka lavas (Fig. 4). Detrital garnet is mostly almandine-pyrope as in Coastal Namib sands, but some almandine-spessartine grains similar to those in Swakop sand are also found (Fig. 5). Staurolite grains are compositionally similar to those in Swakop sand. U/Pb age spectra of detrital zircons are indistinguishable from Orange and Namib sands, showing the same prominent Damara and Namaqua peaks and minor older and younger clusters (Fig. 6).

4.4 Kunene River

Sourced in basement rocks of Angola highlands (De Carvalho et al., 2000) and flowing along the western edge of the fossil Kalahari dune field (Shaw and Goudie, 2002), the Kunene River in Angola carries feldspatho-quartzose sand with K-feldspar > plagioclase ≥ twinned microcline, and poor amphibole > epidote suites including sillimanite (Fig. 3). Its Namibian tributaries draining Neoproterozoic siliciclastic rocks carry feldspatho-quartzose sand with a very poor suite including epidote, amphibole, zircon and Ti-oxides. Tributaries draining the Kunene Anorthosite carry quartzo-feldspathic sand with abundant plutonic rock fragments and twinned plagioclase; the rich heavy-mineral suite includes hornblende and pyroxene. Tributaries draining the Epupa Complex carry feldspatho-quartzose sand with granitoid and high/very-high-rank metamorphic rock fragments including amphibolite, and a very rich hornblende-dominated suite with epidote and minor sillimanite. Kunene River sand close to the mouth is enriched markedly in plagioclase and in plutonic and metamorphic rock fragments, and carries a moderately rich, hornblende > epidote > clinopyroxene > hypersthene heavy-mineral suite.

5. Provenance analysis

Tracing sand dispersal along the coast of Namibia, which contains the world's most spectacular gem diamond placers, has major economic implications (Corbett and Burrell, 2001). And yet provenance studies have not been carried out in the Skeleton Coast, where diamondiferous terraces occur as far as the Kunene mouth. Provenance from Karoo diamictites exposed locally in the Huab, Hoanib, Hoarusib and Kunene catchments was favored by Moore and Moore (2004 p.128), who considered these diamonds as too large to be part of the Orange River dispersion, and thus concluded "*there are no other obvious sources, besides the glacial sedimentary rocks, that can explain this diamond distribution*". Also Skeleton Coast dunes were claimed to be derived from local sources (Lancaster, 1982). Long-distance transport from either the Orange or Kunene mouths, however, could not be tested in the absence of mineralogical data.

In this study, we define the compositional fingerprints of all sand types delivered to coastal Namibia by an integrated set of petrographic and mineralogical parameters (Table 1). The relative importance of long-distance supply from either the Orange or Kunene Rivers versus local supply from hinterland rivers draining the Damara Orogen or Etendeka volcanic province is thus assessed by forward end-member modeling (Garzanti et al., 2012b). Additional entry points of detritus along the coast are identified, and their relative contributions quantitatively determined. In our calculations, local sources of variance (e.g., anomalous heavy-minerals concentration by selective-entrainment effects) were removed by the iterative correction method illustrated in Garzanti et al. (2009). We did not consider micas, which are easily winnowed out of wave and wind-dominated environments. We took into account that sand blown from the shore commonly mixes with river sediments in the coastal plain (e.g., by excluding pyroxene of such foreign origin). Enrichment in harder minerals by breakdown of less durable grains during littoral and eolian transport can be considered negligible (Garzanti et al., in review). Modification of sediment composition by chemical weathering can be safely held as minimal, as indicated by CIA indices ≤ 50 for all analyzed samples (Table 1; Garzanti et al., 2014).

5.1 River sediment fluxes

Sediment is potentially supplied to coastal Namibia by three different fluvial sources: the Orange, the Kunene, and hinterland rivers. For the Orange River, cosmogenic ^{10}Be and ^{26}Al measurements on quartz grains point to catchment-wide erosion rates averaged over millennial time scales of 0.004±0.001 mm/a (Vermeesch et al., 2010), corresponding to sediment loads of 11±2 10^6 tons/a. Detrital fluxes reached up to 90 10^6 tons/a prior to construction of major dams in South Africa (Rooseboom and Harmse, 1979), and huge volumes of sediment dominantly derived from bank erosion and river-bed scour downstream of major dams are still transported during floods (81 10^6 tons in March to May 1988; Bremner et al., 1990). The present estimated rate of sand input to the Namib Sand Sea is ~ 1.1 10^6 tons/a (400,000 m^3/a; Lancaster, 1989), representing a considerable fraction of Orange bedload (estimated to be ~ 5% of total Orange load; Bremner et al., 1990).

The second most important source is the Kunene River, with an estimated sediment load of ~ 9 10^6 tons/a (Bremner and Willis, 1993), but even ephemeral hinterland rivers may carry large volumes of terrigenous detritus to the sea. During the 1934 flood, the Swakop River dumped > 50 10^6 tons of sediment at the mouth, extending the coastline seaward by > 1 km (Bremner and Willis, 1993). Long-term supply from rivers draining the Damara Orogen in the Erongo region can be quantified collectively at ~ 10^6 ton/a, corresponding to catchment-wide erosion rates of 0.003-0.009 mm/a as determined by ^{10}Be and ^{26}Al measurements in quartz. Supply from the small Koigab and Uniab Rivers draining the arid Etendeka plateau is minor (~ 0.05 10^6 tons/a; Bierman and Caffee, 2001).

5.2 Compositional trends

Beach and eolian-dune sands are consistently feldspatho-quartzose to litho-feldspatho-quartzose and rich in volcanic detritus from north of the Orange mouth to Möwe Bay. Sand petrography, heavy minerals, pyroxene chemistry and U-Pb detrital-zircon geochronology concur to indicate that Orange-derived sand not only makes up virtually the whole of the Coastal Namib Erg but carries on to reach the Skeleton Coast and beyond, and remains the major sediment source throughout coastal Namibia. The Orange River, however, is not the unique source of sand, as revealed by subtle successive compositional changes (Table 1). The mineralogy of beach sands changes distinctly north of Walvis Bay, revealing additional local supply from amphibolite-facies metasedimentary rocks of the Damara Inland Branch. Volcanic rock fragments, diluted by metamorphic detritus north of Swakopmund, increase again in the north due to supply from Etendeka lavas. This is manifested macroscopically by volcaniclastic gravel, which becomes abundant on Cape Cross beach and eventually dominant from the Uniab mouth to beyond Möwe Bay, where deflated beaches consist entirely of imbricated basalt and quartz-latite clasts. Beach sands of the Skeleton Coast may show bimodal size distribution of heavy minerals, with pyroxene derived long-distance from the Orange mouth markedly finer-grained than staurolite, sillimanite or garnet derived from proximal Damara metasedimentary sources. Fibrolitic sillimanite is concentrated in coarser size classes also because of settling-equivalence effects (Garzanti et al., 2008).

It is worth noting that all Namibian rivers including the Orange and the Kunene carry similar amounts of quartz to the ocean (50-65% of bulk sand). Conversely, quartz represents 70-80% in most beach and dune sands. Slight quartz enrichment relative to all possible river sources may be ascribed to diverse processes, including mechanical breakdown of labile sedimentary and metamorphic rock fragments, winnowing of micas in high-energy coastal environments, local recycling of Neogene eolianites and repeated cycling from the shelfal to the eolian environment and back during Pleistocene eustatic fluctuations, or quartz concentration on the wide coastal-plain pediment (Bierman and Caffee, 2001).

5.3. Fluvial contributions

The rapid change in heavy-mineral suites north of Walvis Bay indicates that nearly two-thirds of beach sand along the Erongo coast is supplied locally by rivers draining the Inland Branch of the Damara Orogen. Best-fit estimates indicate the Swakop River as the most important local source of detritus by far. The best tracer of Swakop supply is staurolite, derived from metasedimentary rocks exposed in the upper catchment and found in abundance in paleo-Swakop terraces (Van der

Wateren and Dunai, 2001). Contributions from the Omaruru, Ugab and Huab Rivers are minor and not revealed by our data. Omaruru and Ugab sands are both feldspar-rich, and yet feldspars do not increase in beaches downcurrent of their mouths. Instead, the quartz/feldspar ratio tends to increase, hinting at local recycling of quartzose sediments or metasedimentary rocks. Volcanic rock fragments and pyroxene increase north of the Uniab mouth, but detritus from the Etendeka plateau is calculated to represent only ~ 4% of Skeleton Coast beach sand. The Hoanib, Hoarusib and Kunene Rivers carry heavy-mineral suites dominated by epidote or amphibole, markedly different from those of Skeleton Coast sands and Moçâmedes dune (Fig. 3B). Their contribution thus appears to be negligible.

5.4 Eolian contamination

Across the arid coastal plain, where winds blow incessantly and ephemeral rivers flow only sporadically, fluvial bedload remains exposed on the dry channel for long, and is thus contaminated by wind-blown sand to various degrees. This is confirmed by virtually ubiquitous augitic clinopyroxene in fluvial sands of southern and central Namibia, even where volcanic rocks are not exposed in the catchment. The phenomenon, observed for all streams draining into the Namib Erg (Garzanti et al., 2012a), is minor at the Swakop and Omaruru river mouths, where eolian contamination is calculated to account for ≤ 5% and ≤ 2% of the sand fraction, respectively. Instead, it is particularly evident at the Koigab and Uniab river mouths farther north, where dark-coloured volcaniclastic gravel mixes with light-coloured eolian sand. Forward mixing calculations indicate that only ~ 15% of Koigab sand and ~ 10% of Uniab sand at their mouth is derived from Etendeka lavas, the rest being wind-blown from the coast (Koigab) or derived from eolian dunes collapsed during breakthrough episodes (Uniab). Heavy-mineral suites are thus identical to Skeleton Coast dunes (Table 1) not because the Erg is fed by such local rivers, but because their mouths are choked by eolian sands. Bedload at the Huab river mouth also consists chiefly of Etendeka-derived volcaniclastic gravel, whereas fine sand is calculated to be two-thirds windblown from the coast, the remaining third being derived largely from the Damara Orogen and only in minor amounts from

Etendeka lavas. These observations indicate a low sand-generation potential of volcanic source rocks, which provide abundant gravel but little sand to Skeleton Coast beaches.

5.5 The Skeleton Coast Erg and Moçâmedes desert

Very similar detrital modes, clinopyroxene-rich heavy-mineral suites, and virtually the same pyroxene chemistry and U-Pb age distribution of detrital zircons characterize sands of the Orange River, Coastal Namib Erg and Skeleton Coast Erg. Skeleton Coast dunes have only a little less basaltic rock fragments and pyroxene, and a little more garnet, staurolite and tourmaline than Coastal Namib dunes, and are mineralogically closer to the latter than to adjacent beaches (Fig. 7). Long-distance sand contribution from the Orange River is therefore dominant, but not exclusive. Forward-mixing calculations based on framework-petrography and heavy-mineral data indicate that additional sand supply from the Damara Inland Branch, supplied principally by the Swakop River, amounts to 20±3%. Contributions from Etendeka lavas and other rivers draining the Damara Orogen are below the resolution power of our analysis. Finite mixture modelling of zircon-age spectra using the maximum likelihood algorithm (Galbraith and Green, 1990; Sambridge and Compston, 1994) reveals two major components at 550-600 Ma and ~ 1 Ga, and two minor components at 200-300 Ma and ~ 2 Ga (Fig. 6). The mixing proportions of these components in Orange, Namib Erg and Skeleton Coast Erg sands overlap within error, at 29-50%, 41-62%, 3-8%, and 4-15%, respectively. This leaves little room for additional input of non-Orange-derived zircons.

Renewed dominance of Orange-derived sand in the Skeleton Coast Erg suggests that the main sand flux, continuing north of Walvis Bay, impinges again onshore between Toscanini and Torra Bay. From here, Orange-derived sand is blown landward and accumulates in the Skeleton Coast Erg, overwhelming sand blown off local beaches in proportion of about 2:1. New corridors of eolian sand transport form north of the Erongo deflation area, where coastal orientation changes from SE/NW to SSE/NNW similarly to what observed south of the Namib Erg (Fig. 8; Corbett, 1993).

Petrographic modes and heavy-mineral assemblages indistinguishable from those of Skeleton Coast sands characterize dune sand in southern Angola as north as 15°48’ S, indicating that Orange sand transport overwhelms supply from the Kunene River and continues at least as far as 1750 km north of its mouth. This is the longest cell of longshore sand transport documented so far, being for instance three-times longer than the well known Nile cell in the Mediterranean Sea (Inman and Jenkins, 1984). The Amazon cell is of comparable length as mud is concerned (Allison and Lee, 2004), but Amazon sand is not traced to the western Guyana Shelf (Nota, 1958; Imbrie and Van Andel, 1964).

Several climatic and geomorphological factors promote ultra-long-distance sand drift along the Atlantic coast of southern Africa (Fig. 8). These include dominant southerly winds and powerful waves that generate persistent northward longshore currents, hyperarid climate and long coastal stretches without permanent river influx also due to asymmetric drainage inherited from Cretaceous rifting, and smooth shelf bathymetry with lack of submarine canyons that may act as effective conveyor belts of sand offshore.

6. Conclusions

The Orange River is known to represent the dominant source of beach and dune sands in southern coastal Namibia, where the world's richest gem diamond placers are found. Longshore transport was traced to Walvis Bay (Bluck et al., 2007), but dispersal of Orange sand farther north has never been documented so far, and both diamondiferous coastal terraces and dunes of the Skeleton Coast were previously supposed to be fed by local hinterland rivers (Lancaster, 1982; Moore and Moore, 2004). This study combines high-resolution petrographic, mineralogical, geochemical and geochronological techniques to demonstrate that Orange-derived sediments are transported under the influence of persistent longshore currents for at least 1750 km north of its mouth to as far as southern Angola, and represent the dominant source for the Skeleton Coast Erg and Moçâmedes Desert. Differently from Coastal Namib dunes that are Orange-derived entirely, contributions from metamorphic rocks of the Damara Orogen are significant for Skeleton Coast dunes, which contain somewhat less pyroxene and more garnet and staurolite. Forward-mixing calculations indicate that ≤ 20% of the sand is derived from the Swakop River. Rivers draining the Etendeka volcanic province provide pebbles and cobbles to gravel-dominated beaches of the Skeleton Coast, but only ~ 4% of the sand in sandy beaches. River mouths are chocked by eolian sand either blown from the sea or eroded from the Erg during episodic floods, and their contribution to the dunes is negligible. Dominance of Orange-derived detritus all along Namibian shores imply that diamonds found in beach placers of northern Namibia are derived long-distance from the Orange mouth, rather than locally or from Angola via the Kunene River.

ACKNOWLEDGMENTS

We warmly thank John Compton and Gonzalo Blanco for their critical reviews, Florian Kober and Charlie Bristow for help collecting Skeleton Coast samples, Alcides Pereira, Mariella Boni, Luciana Ciceri, Fernand Vermeesch and Dany Kerckhove for providing river and dune sands, and Marcello Serracino for maintaining the EMP perfectly working.

FIGURE CAPTIONS

Figure 1. Topography, climate and geology of coastal Namibia, with location of the studied sand samples. Climatic zones after Kottek et al. (2006). **Mesoproterozoic** (Becker et al., 2006): K= Kunene intrusive complex; NB= Namaqua Belt; R= Rehoboth terrane; S= Sinclair Group. **Kaoko Belt** (Gray et al., 2008): WK= Western Zone; CK= Central Zone; EK= Eastern Zone; e= Epupa metamorphic complex; k= Kamanjab basement; o= Otavi carbonates. **Inland Branch** (Jung and Mezger, 2003): NZ= Northern Zone, including the Ugab Zone (u); CZ= Central Zone, where partial-melting conditions were reached and granites are abundant; SZ= Southern Zone, dominated by metasediments between the staurolite-in and staurolite-out/sillimanite-in isograds. **Sedimentary and volcanic covers**: N= Nama Group; n= Naukluft Nappes; Ks= Karoo sediments; Kb= Karoo basalts; E= Etendeka lavas.

Figure 2. Sands of Coastal Namibia. Both Coastal Namib (**A**) and Skeleton Coast sands (**E**, **F**), are rich in volcanic rock fragments (Lv) and clinopyroxene (p) derived from the Orange River. Supply from the Swakop River (**B**; b= biotite, g= garnet, s= staurolite) is revealed by decreasing volcanic detritus and common staurolite in beaches of the Erongo region (**D**). Coarse-grained volcanic rock fragments mix with fine-grained eolian sand at the Koigab river mouth (**C**). All photos with crossed polars; blue bar = 250 µm.

Figure 3. Sand petrography and mineralogy. **A**) Coastal Namib and Skeleton Coast sands have similar bulk-sediment composition (Q= quartz; F= feldspar; L= lithic fragments), and are somewhat enriched in quartz relative to all potential river sources. **B**) Heavy minerals are better tracers of sand dispersal. Beaches of the Erongo region are rich in staurolite and garnet derived from amphibolite-facies Damara metasedimentary rocks. Instead, Skeleton Coast dunes are nearly as pyroxene-rich as Coastal Namib sands, revealing provenance from the Orange with additional garnet and staurolite supplied largely via the Swakop River. Contributions from the Kunene, Hoanib and Hoarusib Rivers, carrying mostly amphibole and epidote, are ruled out.

Figure 4. Pyroxene grains as provenance tracers. Augites with subordinate pigeonites derived via the Orange River from Karoo basalts exposed in faraway Lesotho highlands are dominant throughout coastal Namibia. They contaminate Swakop sand at the river mouth and accumulate in the Skeleton Coast Erg after multistep fluvial and longshore transport exceeding 3600 km overall. Augites and pigeonites from Etendeka basalts and quartz-latites have distinct composition (e.g., lower Mg#). Their presence is negligible in Skeleton Coast dunes, which do contain a few diopsides as those found in Swakop sand and shed from impure Damara metacarbonates.

Figure 5. Garnet grains as provenance tracers. Coastal Namib and Swakop River sands contain garnets derived from both medium-grade (*type B* of Morton and Mange, 2007) and high-grade metasedimentary rocks (*type A*). Although compositions largely overlap, high-Mn grains from lower-amphibolite-facies metasediments (*type Bii*) are more common in Swakop sands. Garnets in Skeleton Coast and Coastal Namib sands overlap completely. X_{Fe}, X_{Mg}, X_{Ca} and X_{Mn} are molecular proportions of Fe^{2+}, Mg, Ca and Mn. Fields in ternary plots after Andò et al. (2014) and references therein (X_{Mg} is at the apex of both triangles).

Figure 6. Zircon grains as provenance tracers. U-Pb age distributions in Orange River, Coastal Namib Erg and Skeleton Coast Erg sands are shown as histograms and Kernel Density Estimates (plots produced with DensityPlotter 2.6 using a bandwidth of 40 Ma and a binwidth of 200 Ma; Vermeesch, 2012). Vertical arrows mark the results of a normal mixture modelling calculation using the maximum likelihood algorithm of Galbraith and Green (1990). The six age spectra are nearly identical, indicating a common source.

Figure 7. Provenance analysis with compositional biplot (Gabriel, 1971; www.compositionaldata.com). All major petrographic and mineralogical parameters are considered in the diagram, which defines a continuous trend from the Orange to the Swakop end-members. Coastal Namib sands lie close to the Orange, and Erongo beaches close to the Swakop, with Skeleton Coast beaches in between. Skeleton Coast dunes define a small field within that of Coastal Namib dunes. All other rivers draining Etendeka lavas or the Damara Orogen lie outside the defined

trend and their contribution is undetected. Supply from the Kunene River is ruled out even for the Moçâmedes dune in southern Angola. The length of each ray is proportional to the variability of the corresponding compositional parameter in the data set. If the angle between two rays is close to 0°, 90°, or 180°, then the corresponding parameters are directly correlated, uncorrelated, or inversely correlated, respectively. The first and second principal components account for 25% and 23% of total variance. Q= quartz; KF= K-feldspar; P= plagioclase; L= lithic grains (Lv= volcanic; Ls= sedimentary; Lm= metamorphic). HMC= heavy-mineral concentration.

Figure 8. Ultra-long distance sediment dispersal from the Orange mouth to southern Angola. **A**) Northward-drifting sand accumulates by wave refraction north of headlands and is conveyed by onshore winds in linear corridors of barchan dunes connecting with the Namib Sand Sea (redrawn after Spaggiari et al., 2006). **B**) By the same processes Orange-derived sand piles up in the Skeleton Coast Erg and in the Moçâmedes Desert much farther to the north.

Table 1. Sand petrography and mineralogy in coastal Namibia and southern Angola. N°= number of samples; Q= quartz; KF= K-feldspar; P= plagioclase; L= lithic grains (Lv= volcanic; Ls= sedimentary; Lm= metamorphic). MI and MI*= Metamorphic Indices, ranging respectively from 0 (detritus from sedimentary and volcanic rocks) or 100 (detritus from very low-grade metamorphic rocks) to 500 (detritus from high-grade metamorphic rocks; Garzanti and Vezzoli, 2003). HMC= Heavy Mineral Concentration (Garzanti and Andò, 2007). ZTR= zircon + tourmaline + rutile; Ap= apatite; Ttn= titanite; Ep= epidote-group; Grt= garnet; St= staurolite; SKA= sillimanite + kyanite + andalusite; Amp= amphiboles; Px= pyroxenes; &= other transparent heavy minerals (brookite, anatase, olivine, occasionally monazite or chloritoid). The Chemical Index of Alteration (CIA; Nesbitt and Young, 1982), calculated by using molecular proportions of Ca, Na and K in silicates, ranges from 50 for unweathered feldspars to 100 for kaolinite.

REFERENCES

Ahrendt, H., Hunziker, J.C., Weber, K., 1978. Age and degree of metamorphism and time of nappe emplacement along the southern margin of the Damara Orogen, Namibia (SW-Africa). Geologische Rundschau, 67, 719-742.

Allison, M.A., Lee, M.T., 2004. Sediment exchange between Amazon mudbanks and shore-fringing mangroves in French Guiana. Marine Geology, 208, 169-190.

Andò, S., Morton, A., Garzanti, E. 2014. Metamorphic grade of source rocks revealed by chemical fingerprints of detrital amphibole and garnet. In: Scott, R.A., Smyth. H.R., Morton, A.C., Richardson, N. (Eds.), Sediment provenance studies in hydrocarbon exploration and production. Geological Society London, Special Publication 386, 351-371.

Becker, T., Schreiber, U., Kampunzu, A.B., Armstrong, R., 2006. Mesoproterozoic rocks of Namibia and their plate tectonic setting. Journal of African Earth Sciences, 46, 112-140.

Bierman, P.R., Caffee, M. 2001. Slow rates of rock surface erosion and sediment production across the Namib desert and Escarpment, Southern Africa. American Journal of Science, 301, 326-358.

Blanco, G., Germs, G.J.B, Rajesh, H.M, Chemale, F., Dussin, I.A., Justino, D. 2011. Provenance and paleogeography of the Nama Group (Ediacaran to early Palaeozoic, Namibia): petrography, geochemistry and U–Pb detrital zircon geochronology. Precambrian Research, 187, 15-32.

Bluck, B.J., Ward, J.D., Cartwright, J., Swart, R., 2007. The Orange River, southern Africa: an extreme example of a wave-dominated sediment dispersal system in the South Atlantic Ocean. Journal of the Geological Society London, 164, 341-351.

Borg, G., 1988. The Koras–Sinclair–Ghanzi rift in southern Africa: volcanism, sedimentation, age relationships and geophysical signature of a late middle Proterozoic rift system. Precambrian Research, 38, 75-90.

Bremner, J.M., Rogers, J., Willis J.P., 1990. Sedimentological aspects of the 1988 Orange River floods. Transactions of the Royal Society of South Africa, 47, 247-294.

Bremner, J.M., Willis J.P., 1993. Mineralogy and geochemistry of the clay fraction of sediments from the Namibian continental margin and the adjacent hinterland. Marine Geology, 115, 85-116.

Cockburn, H.A.P., Brown, R.W., Summerfield, M.A., Seidl, M.A., 2000. Quantifying passive margin denudation and landscape development using a combined fission-track thermochronology and cosmogenic isotope analysis approach. Earth and Planetary Science Letters, 179, 429-435.

Compton, J.S., Wigley, R., McMillan, I.K., 2004. Late Cenozoic phosphogenesis on the western shelf of South Africa in the vicinity of the Cape Canyon. Marine Geology, 206, 19-40.

Compton, J., Herbert, C., Schneider, R., 2009. Organic-rich mud on the western margin of southern Africa: nutrient source to the Southern Ocean? Global Biogeochemical Cycles, 23, GB4030, doi:10.1029/2008GB003427.

Compton, J.S., Herbert, C.T., Hoffman, M.T., Schneider, R.R., Stuut, J.B., 2010. A tenfold increase in the Orange River mean Holocene mud flux: implications for soil erosion in South Africa. The Holocene, 20, 115-122.

Corbett, I., 1993. The modern and ancient pattern of sandflow through the southern Namib deflation basin. International Association of Sedimentology, Special Publication 16, 45-60.

Corbett, I., Burrell, B., 2001. The earliest Pleistocene(?) Orange River fan-delta: an example of successful exploration delivery aided by applied Quaternary research in diamond placer sedimentology and palaeontology. Quaternary International, 82, 63-73.

De Carvalho, H., Tassinari, C., Alves, P.H., Guimarães, F., Simões, M.C., 2000. Geochronological review of the Precambrian in western Angola: links with Brazil. Journal of African Earth Sciences, 31, 383-402.

Ewart, A., Marsh, J.S. Milner, S.C., Duncan, A.R., Kamber, B.S., Armstrong, R.A., 2004. Petrology and geochemistry of Early Cretaceous bimodal continental flood volcanism of the NW Etendeka, Namibia. Journal of Petrology, 45, 59-138.

Frimmel, H.E., Frank, W., 1998. Neoproterozoic tectono-thermal evolution of the Gariep Belt and its basement, Namibia and South Africa. Precambrian Research, 90, 1-28.

Gabriel, K.R. 1971. The biplot graphic display of matrices with application to principal component analysis. Biometrika, 58, 453-467.

Galbraith, R.F., Green, P.F., 1990. Estimating the component ages in a finite mixture. Nuclear tracks and radiation measurements, 17, 197-206.

Galehouse, J.S., 1971. Point counting. In: Carver, R.E. (Ed.), Procedures in sedimentary petrology. Wiley, New York, pp. 385-407.

Garzanti, E., Andò, S., 2007. Heavy-mineral concentration in modern sands: implications for provenance interpretation. In: Mange, M.A., Wright, D.T. (Eds.), Heavy Minerals in Use, Developments in Sedimentology Series, 58. Elsevier, Amsterdam, pp. 517-545.

Garzanti, E., Vezzoli, G. 2003. A classification of metamorphic grains in sands based on their composition and grade. Journal of Sedimentary Research, 73, 830-837.

Garzanti, E., Andò, S., Vezzoli, G., 2008. Settling-equivalence of detrital minerals and grain-size dependence of sediment composition. Earth and Planetary Science Letters, 273, 138-151.

Garzanti, E., Andò, S., Vezzoli, G., 2009. Grain-size dependence of sediment composition and environmental bias in provenance studies. Earth and Planetary Science Letters, 277, 422-432.

Garzanti, E., Andò, S., Vezzoli, G., Lustrino, M., Boni, M., Vermeesch, P., 2012a. Petrology of the Namib sand sea: long-distance transport and compositional variability in the wind-displaced Orange Delta. Earth-Science Reviews, 11, 173-189.

Garzanti, E., Resentini, A., Vezzoli, G., Andò, S., Malusà, M., Padoan, M., 2012b. Forward compositional modelling of Alpine orogenic sediments. Sedimentary Geology, 280, 149-164.

Garzanti. E., Vermeesch, P., Padoan, M., Resentini, A., Vezzoli, G., Andò, S., 2014. Provenance of passive-margin sand (southern Africa). The Journal of Geology, 122, 17-42.

Garzanti, E., Resentini, A., Andò, S., Vezzoli, G., Vermeesch, P., in review. Physical controls on sand composition and relative durability of detrital minerals during long-distance littoral and eolian transport (coastal Namibia). Submitted to Sedimentology 2/3/2014.

Goscombe, B., Hand, M., Gray, D., 2003a. Structure of the Kaoko belt: progressive evolution of a classic transpressional orogen. Journal of Structural Geology, 25, 1049-1081.

Goscombe, B., Hand, M., Gray, D., Mawby, J., 2003b. The metamorphic texture of a transpressional orogen, the Kaoko belt Namibia. Journal of Petrology, 44, 679-711.

Gray, D.R., Foster, D.A., Meert, J.G., Goscombe, B.D., Armstrong, R., Trouw, R.A.J., Passchier, C.W., 2008. A Damara Orogen perspective on the assembly of southwestern Gondwana. In: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B., De Wit, M.J. (Eds.), West Gondwana: pre-Cenozoic correlations across the South Atlantic region. Geological Society of London, Special Publication 294, 257-278.

Guillocheau, F., Rouby, D., Robin, C., Helm, C., Rolland, N., Le Carlier de Veslud, C., Braun, J., 2012. Quantification and causes of the terrigeneous sediment budget at the scale of a continental margin: a new method applied to the Namibia’s South Africa margin. Basin Research, 24, 3-30.

Hartmann, K., Brunotte, E., 2008. The genesis and current reshaping of dunes at the eastern margin of the northern Namib Desert (Hartmann Valley, NW Namibia). Modelled wind-flow patterns, multi-temporal aerial photograph analysis and anthropogenic morphodynamics. Zeitschrift für Geomorphologie, 52, 1-14.

Hartmann, O., Hoffer, E., Haack, U., 1983. Regional metamorphism in the Damara orogen: interaction of crustal motion and heat transfer. Geological Society of South Africa, Special Publication 11, 233-241.

Heine, K., 2005. Holocene climate of Namibia: a review based on geoarchives. African Study Monographs, Supplement 30, 119-133.

Hoal, B.G., 1993. The Proterozoic Sinclair Sequence in southern Namibia: intracratonic rift or active continental margin setting? Precambrian Research, 63, 143-162.

Imbrie, J., Van Andel, T.H., 1964. Vector analysis of heavy-mineral data. Geological Society of America Bulletin, 75, 1131-1156.

Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., Sares, S.W., 1984. The effect of grain size on detrital modes: a test of the Gazzi-Dickinson point-counting method. Journal of Sedimentary Petrology, 54, 103-116.

Inman, D.L., Jenkins, S.A., 1984. The Nile littoral cell and man's impact on the coastal zone of the southeastern Mediterranean. Scripps Institution of Oceanography, Reference Series 31, pp. 1-43.

Jacobs, J., Pisarevsky, S., Thomas, R.J., Becker, T., 2008. The Kalahari Craton during the assembly and dispersal of Rodinia. Precambrian Research, 160, 142-158.

Jacobson, P.J., Jacobson, K.M., Seely, M.K., 1995. Ephemeral rivers and their catchments: sustaining people and development in western Namibia. Desert Research Foundation of Namibia, Windhoek, 160 pp.

Jerram, D., Mountney, N., Holzförster, F., Stollhofen, H., 1999. Internal stratigraphic relationships in the Etendeka Group in the Huab Basin, NW Namibia: understanding the onset of flood volcanism. Journal of Geodynamics, 28, 393-418.

Jung, S., Mezger, K., 2003. Petrology of basement-dominated terranes: I. Regional metamorphic T–t path from U–Pb monazite and Sm–Nd garnet geochronology (Central Damara orogen, Namibia). Chemical Geology, 198, 223-247.

Kocurek, G., Lancaster, N., Carr, M., Frank, A., 1999. Tertiary Tsondab Sandstone Formation: preliminary bedform reconstruction and comparison to modern Namib sand sea dunes. Journal of African Earth Sciences, 29, 629-642.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F. 2006. World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, 15, 259-263.

Krapf, C.B.E., Stollhofen, H., Stanistreet, I.G., 2003. Contrasting styles of ephemeral river systems and their interaction with dunes of the Skeleton Coast erg (Namibia). Quaternary International, 104, 41-52.

Krapf, C.B.E., Stanistreet, I.G., Stollhofen, H., 2005. Morphology and fluvio-aeolian interaction of the tropical latitude, ephemeral braided-river dominated Koigab Fan, north-west Namibia. International Association of Sedimentologists, Special Publication 35, 99-120.

Lancaster, N., 1982. Dunes on the Skeleton Coast, Namibia (South West Africa): geomorphology and grain size relationships. Earth Surface Processes and Landforms, 7, 575-587.

Lancaster, N., 1985. Winds and sand movement in the Namib sand sea. Earth Surface Processes and Landforms, 10, 607-619.

Lancaster, N., 1989. The Namib sand sea: dune forms, processes, and sediments. Balkema, Rotterdam, 200 pp.

Lustrino, M., Melluso, L., Brotzu, P., Gomes, C.B., Morbidelli, L., Muzio, R., Ruberti, E., Tassinari, C.C.G., 2005. Petrogenesis of the Early Cretaceous Valle Chico igneous complex (SE Uruguay): relationships with Paraná-Etendeka magmatism. Lithos, 82, 407-434.

Mange, M.A., Morton, A.C., 2007. Geochemistry of heavy minerals. In: Mange, M.A., Wright, D. T. (Eds), Heavy Minerals in Use. Elsevier, Amsterdam, Developments in Sedimentology, 58, pp. 345-391.

Martin, H., Porada, H., 1977. The intracratonic branch of the Damara orogen in South West Africa. Precambrian Research, 5, 311-357.

Miller, R.M., 2008, The geology of Namibia. Ministry of Mines and Energy, Windhoek (3 volumes).

Moore, J.M., Moore, A.E. 2004. The roles of primary kimberlitic and secondary Dwyka glacial sources in the development of alluvial and marine diamond deposits in Southern Africa. Journal of African Earth Sciences, 38, 115-134.

Morin, E., Grodek, T., Dahan, O., Benito, G., Kulls, C., Jacoby, Y., Van Langenhove, G., Seely, M., Enzel, Y., 2009. Flood routing and alluvial aquifer recharge along the ephemeral arid Kuiseb River, Namibia. Journal of Hydrology, 368, 262-275.

Nesbitt, H.W., Young, G.M., 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. Nature, 299, 71-717.

Nota, D.J.G., 1958. Sediments of the western Guiana Shelf. Mededelingen van de Landbouwhogeschool te Wageningen, 58, pp. 1-98.

Puhan, D. 1983. Metamorphism of siliceous dolomites of the central and southern part of the Damara Orogen. In: Henno, M., Eder, F.W. (Eds.), Intracontinental fold belts: case studies in the Variscan Belt of Europe and the Damara Belt in Namibia. Springer, Berlin, pp. 767-784.

Rogers, J., 1977. Sedimentation on the continental margin off the Orange River and the Namib desert. Geology Survey/University of Cape Town Marine Geosciences Group Bulletin, 7, pp.1-162.

Rogers, J., Bremner, J.M., 1991. The Benguela ecosystem. Part VII. Marine-geological aspects. In: Barnes, M. (Ed.), Oceanography and marine biology, an annual review, Aberdeen University Press, vol. 29, pp.1-86.

Rogers, J., Rau, A.J., 2006. Superficial sediments of the wave-dominated Orange River delta and the adjacent continental margin off southwestern Africa. African Journal of Marine Sciences, 28, 511-524.

Rooseboom, A., Harmse, H.J. von M., 1979. Changes in sediment load of the Orange River during the period 1929–1969. Hydrology of areas of low precipitation. International Association of Hydrological Sciences, Publication 128, 459-479.

Sambridge, M.S., Compston, W., 1994. Mixture modeling of multi-component data sets with application to ion-probe zircon ages. Earth and Planetary Science Letters, 128, 373-390.

Schmitt, A.K., Emmermann, R., Trumbull, R.B., Bühn, B., Henjes-Kunst, F., 2000. Petrogenesis and ^{40}Ar/^{39}Ar geochronology of the Brandberg Complex, Namibia: evidence for a major mantle contribution in metaluminous and peralkaline granites. Journal of Petrology, 51, 1207-1239.

Shaw, A., Goudie, A.S., 2002. Geomorphological evidence for the extension of the Mega-Kalahari into south-central Angola. South African Geographical Journal, 84, 182-194.

Spaggiari, R.I., Bluck, B.J., Ward, J.D., 2006. Characteristics of diamondiferous Plio-Pleistocene littoral deposits within the palaeo-Orange River mouth, Namibia. Ore Geology Reviews, 28, 475-492.

Stanistreet, I.G., Stollhofen, H., 2002. Hoanib River flood deposits of Namib Desert interdunes as analogues for thin permeability barrier mudstone layers in aeolianite reservoirs. Sedimentology, 49, 719-736.

Strohbach, B.J., 2008. Mapping the major catchments of Namibia. Agricola, 18, 63-73.

Svendsen, J., Stollhofen, H., Krapf, C.B.E., Stanistreet, I.G., 2003. Mass and hyperconcentrated flow deposits record dune damming and catastrophic breakthrough of ephemeral rivers, Skeleton Coast Erg, Namibia. Sedimentary Geology, 160, 7-31.

Van der Wateren, F.M., Dunai, T.J., 2001. Late Neogene passive margin denudation history - cosmogenic isotope measurements from the central Namib desert. Global Planetary Change, 30, 271-307.

Van Zinderen Bakker, E.M., Mercer, J.H., 1986. Major late Cainozoic climatic events and palaeoenvironmental changes in Africa viewed in a worldwide context. Palaeogeography Palaeoclimatology Palaeoecology, 56, 217-235.

Vermeesch, P., 2012. On the visualisation of detrital age distributions. Chemical Geology, 312, 190-194.

Vermeesch, P., Fenton, C.R., Kober, F., Wiggs, G.F.S., Bristow, C.S., Xu, S., 2010. Sand residence times of one million years in the Namib Sand Sea from cosmogenic nuclides. Nature Geosciences, 3, 862-865.

Ward, J.D., 1987. The Cenozoic succession in the Kuiseb Valley, Central Namib Desert. Geological Survey of Namibia, Memoir 9, pp. 1-45.

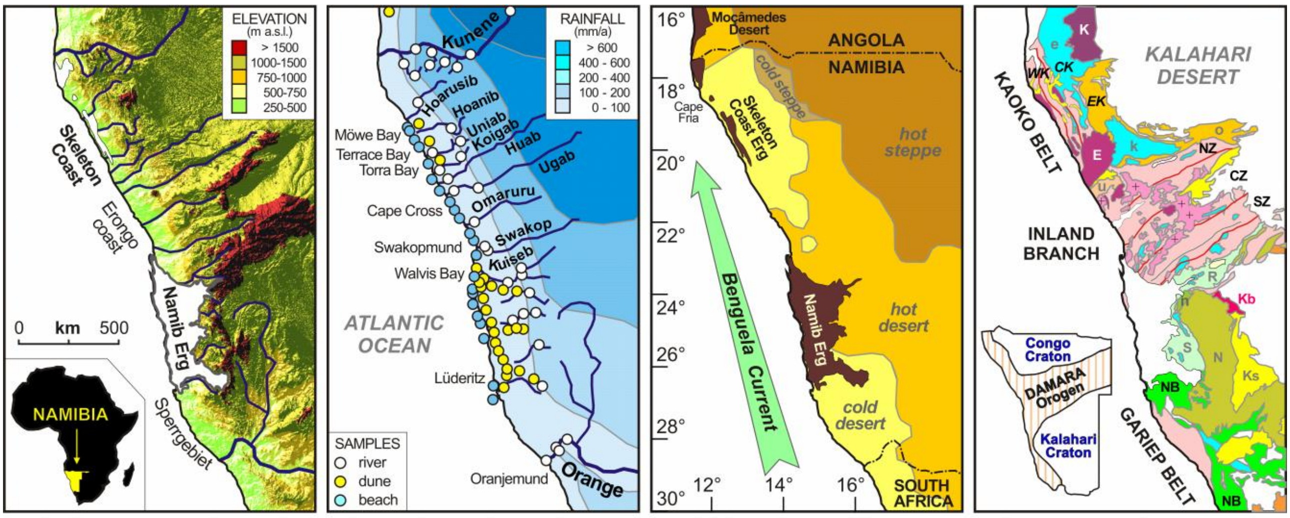
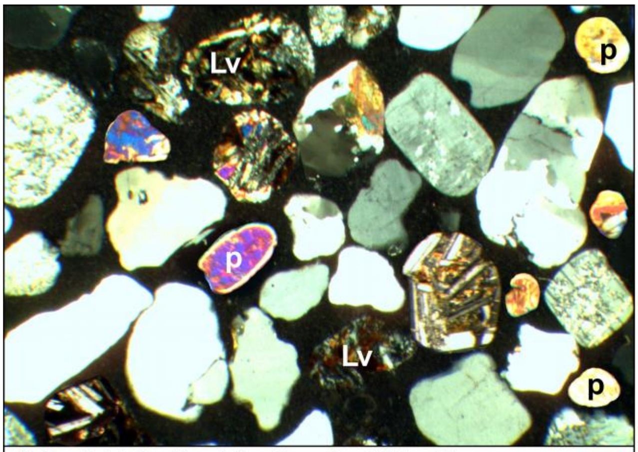
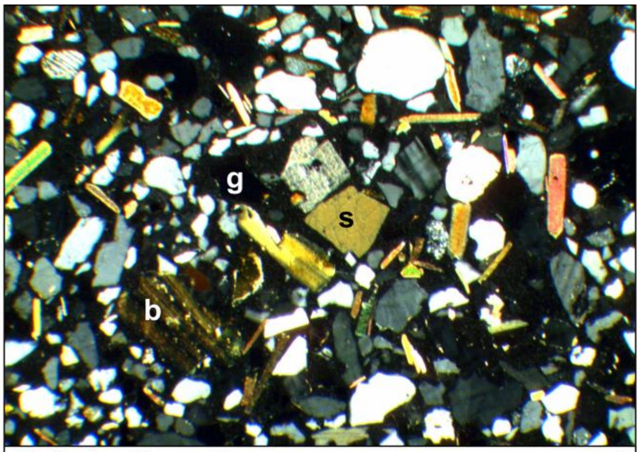


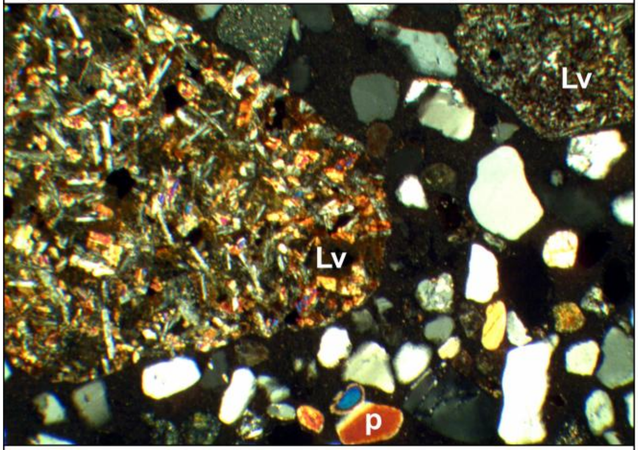
Figure 1 Skeleton



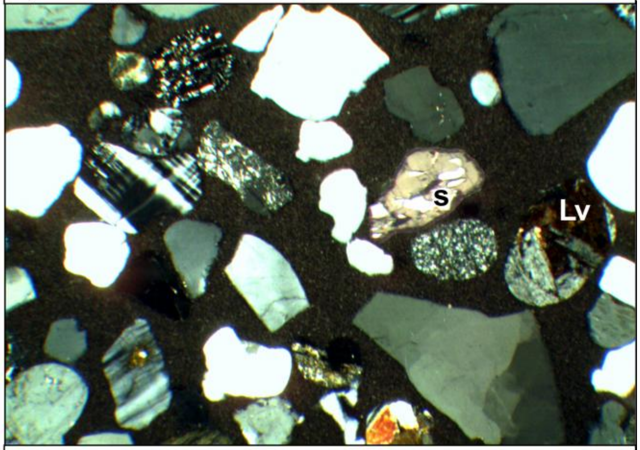
A) Sandwich Bay beach (northern Coastal Namib)



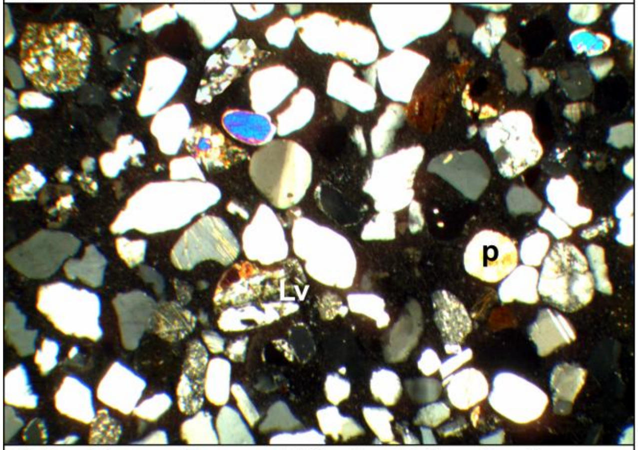
B) Swakop River mouth



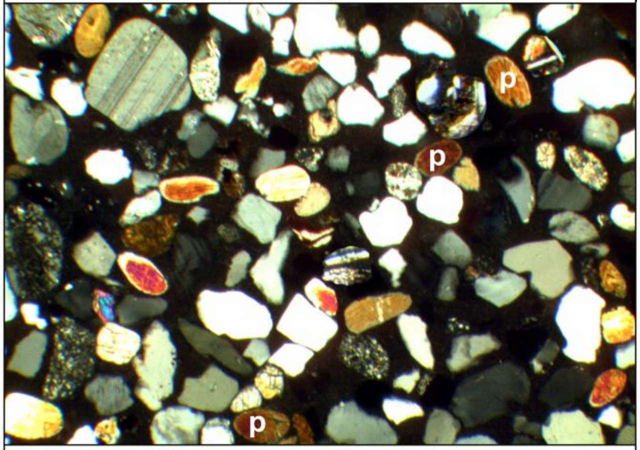
C) Koigab River mouth



D) Beach at Mile 14 (Erongo region)



E) Beach between Terrace and Möwe Bay (Skeleton Coast)



F) Dune east of Torra Bay (Skeleton Coast Erg)

Figure 2 Skeleton

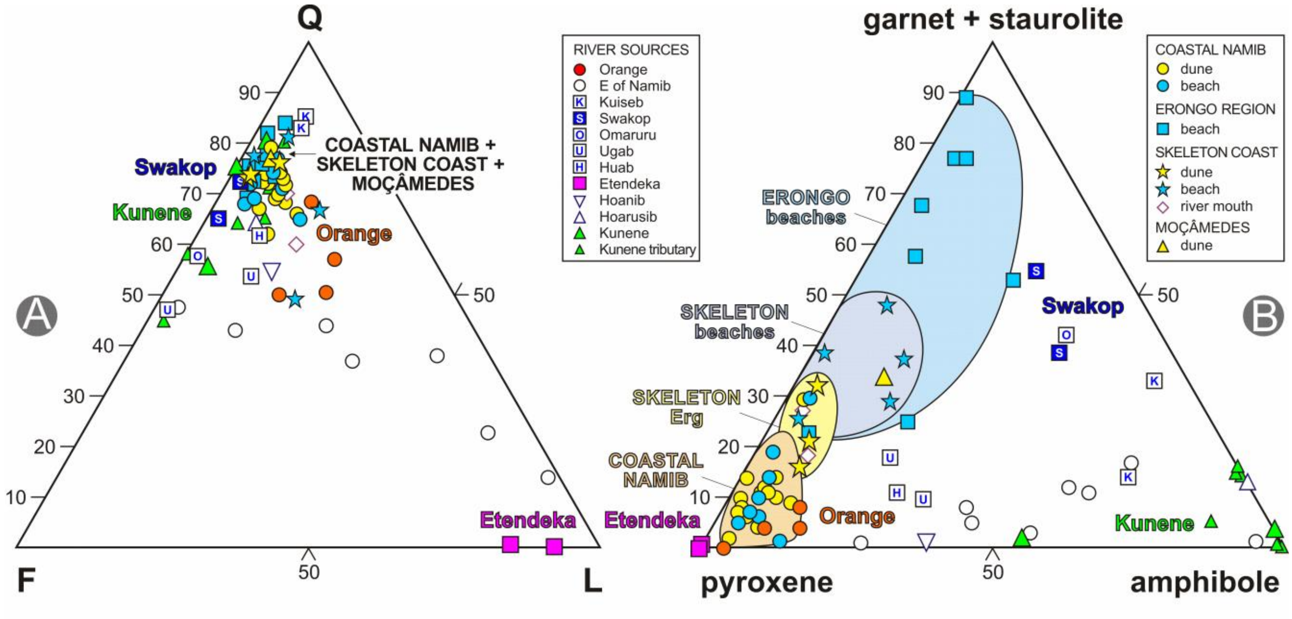


Figure 3 Skeleton

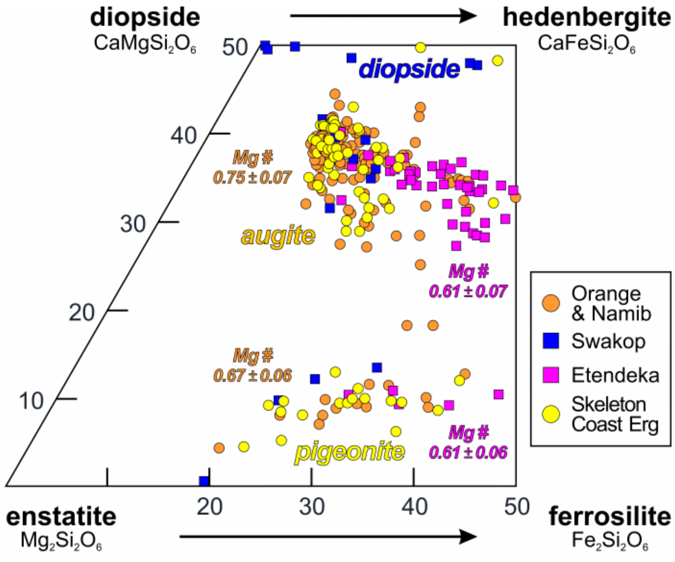


Fig. 4 Skeleton

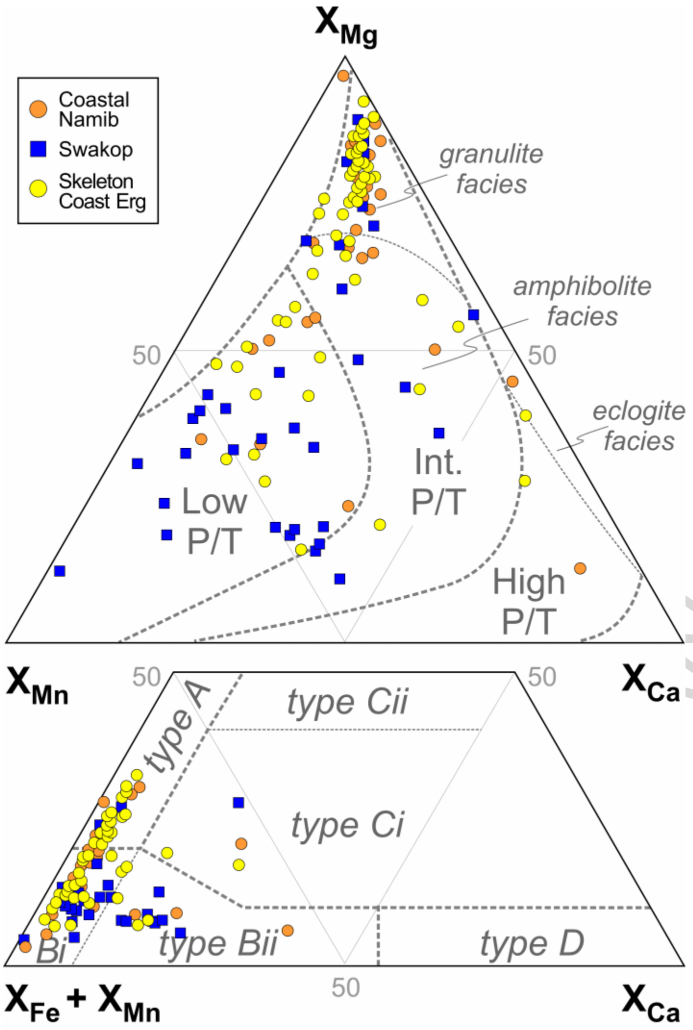


Fig. 5 Skeleton

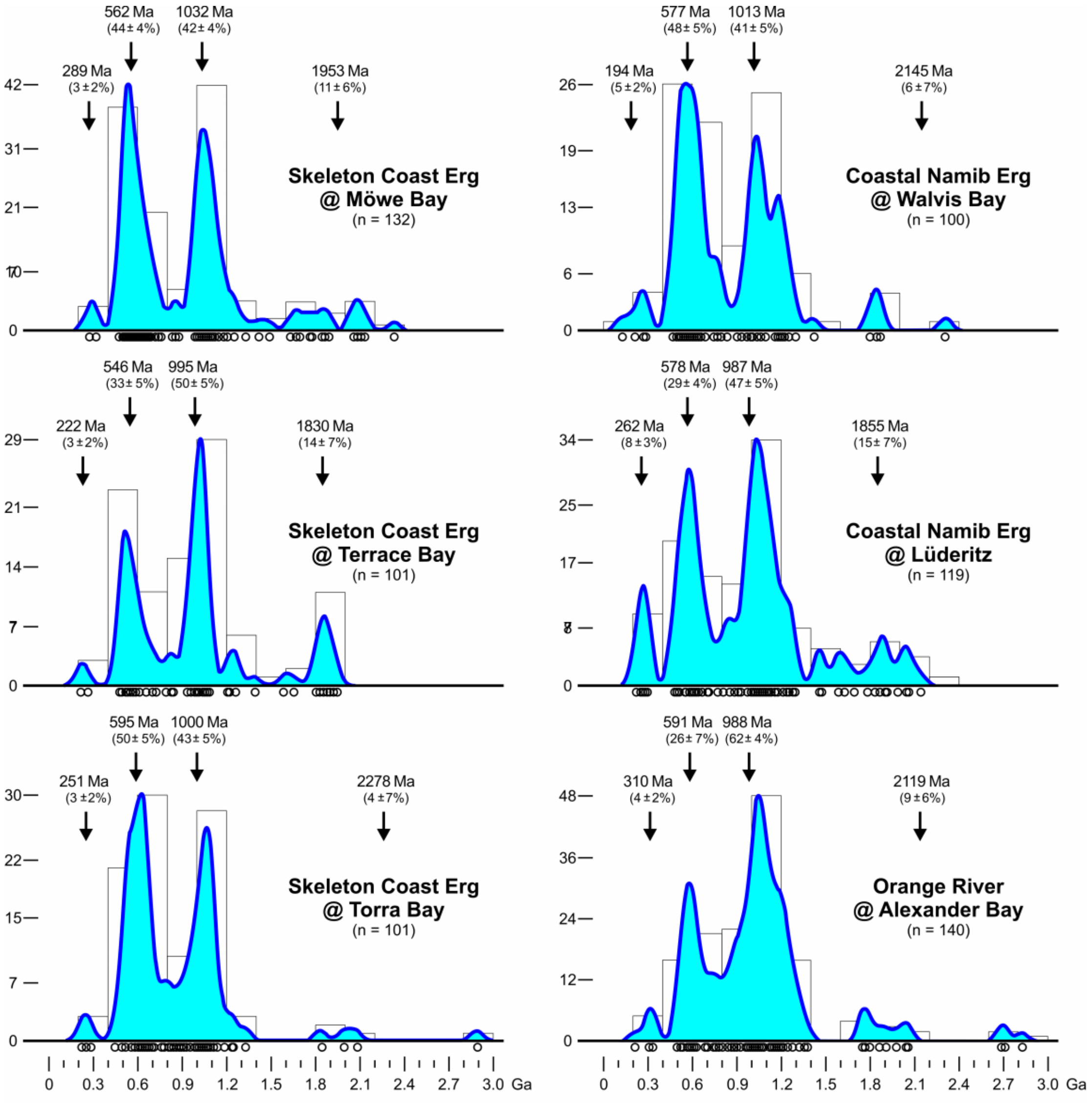


Figure 6 Skeleton

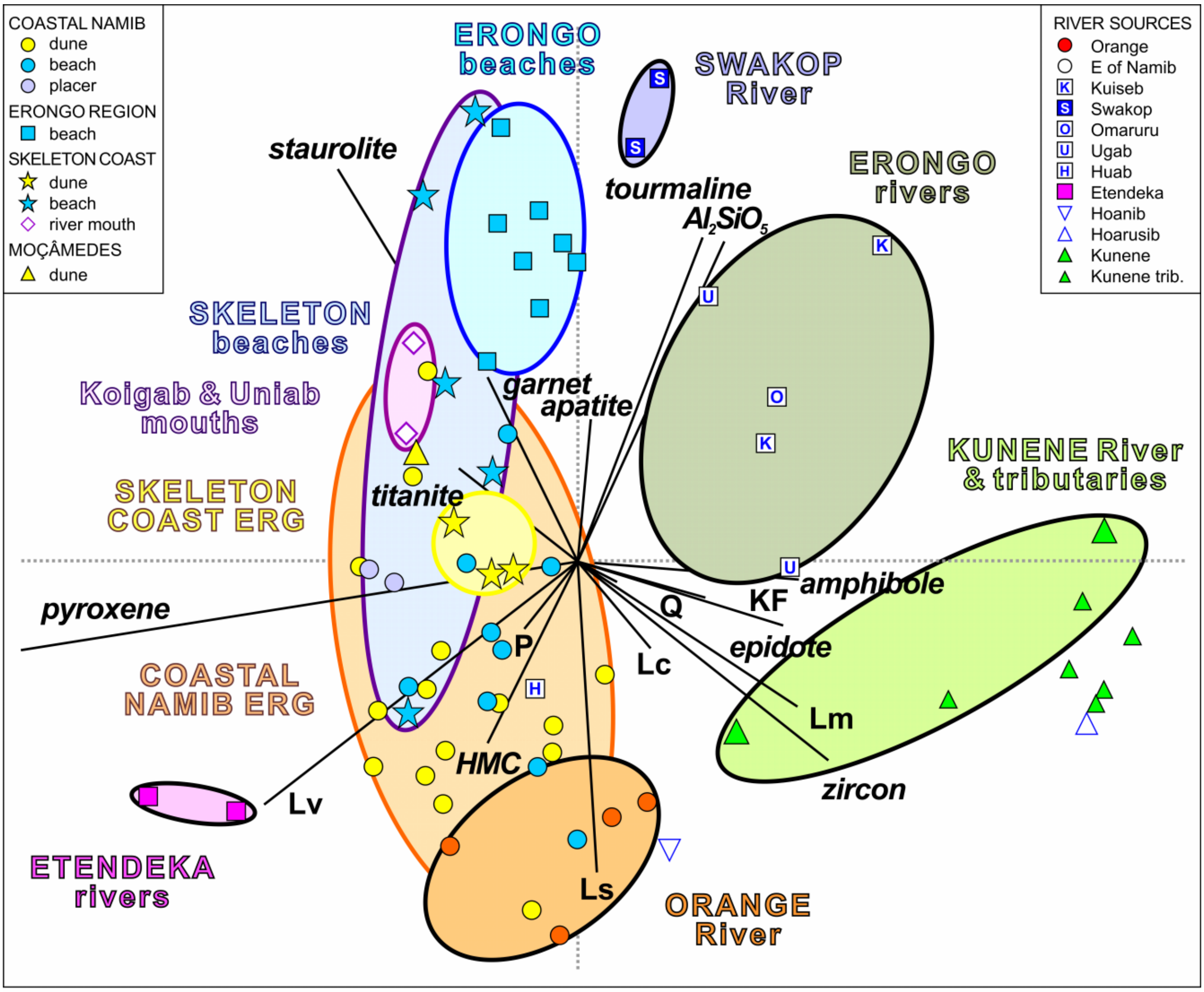


Figure 7 Skeleton

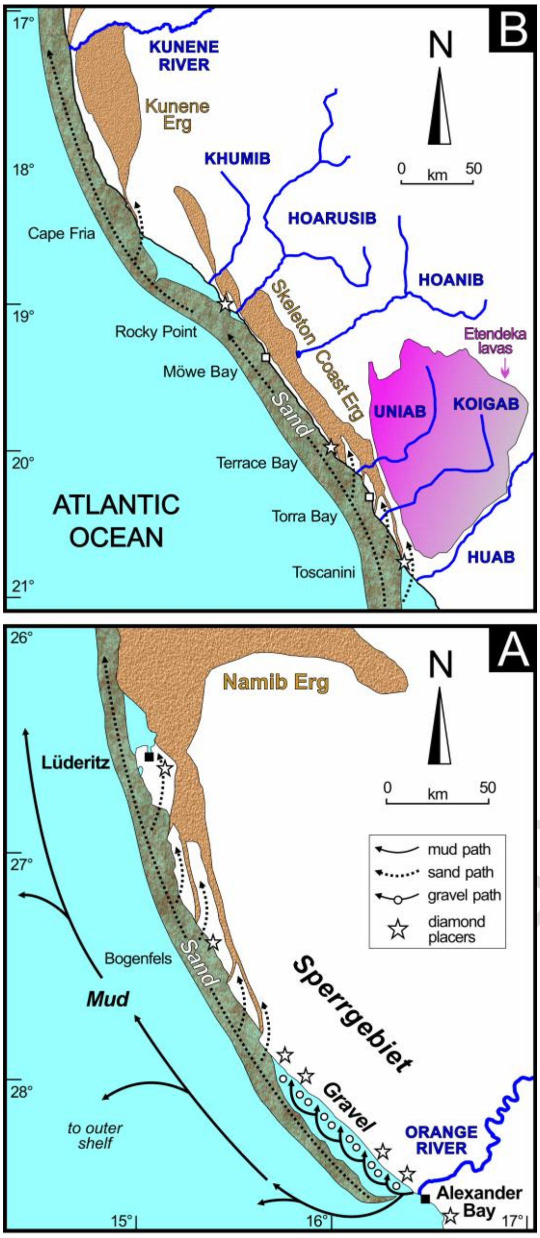


Figure 8 Skeleton

Table 1

	N°	Q	KF	P	Lv	Ls	Lm	tot	MI*	MI	HMC	ZTR	Ap	Ttn	Ep	Grt	St	SKA	Amp	Px	&	tot	CIA
Orange River	4	**57**	**7**	**14**	**9**	**10**	**3**	100.0	**228**	**56**	**7**	**2**	**1**	**1**	**14**	**3**	**0**	**0**	**8**	**70**	**2**	100.0	**49**
		9	*1*	*6*	*5*	*7*	*1*		*42*	*10*	*2*	*1*	*1*	*1*	*14*	*2*	*0*	*0*	*2*	*22*	*3*		*3*
Coastal Namib	24	**72**	**8**	**13**	**6**	**1**	**0**	100.0	**275**	**27**	**10**	**1**	**0**	**1**	**5**	**12**	**1**	**1**	**5**	**76**	**0**	100.0	**46**
(dunes+beaches)		*4*	*2*	*2*	*3*	*1*	*0*		*94*	*19*	*19*	*1*	*0*	*1*	*4*	*13*	*1*	*1*	*3*	*13*	*0*		*3*
Erongo coast	8	**76**	**6**	**13**	**2**	**1**	**1**	100.0	**355**	**121**	**3**	**6**	**1**	**1**	**4**	**39**	**12**	**5**	**9**	**25**	**0**	100.0	**51**
(beaches)		*5*	*2*	*3*	*2*	*1*	*0*		*101*	*105*	*3*	*3*	*1*	*1*	*2*	*25*	*5*	*5*	*8*	*14*	*0*		*0*
Skeleton Coast	5	**70**	**7**	**12**	**10**	**1**	**0**	100.0	**383**	**35**	**6**	**4**	**1**	**1**	**6**	**27**	**3**	**2**	**8**	**47**	**0**	100.0	**49**
(beaches)		*13*	*4*	*2*	*9*	*1*	*0*		*165*	*56*	*7*	*1*	*1*	*1*	*2*	*9*	*2*	*3*	*6*	*10*	*0*		*2*
Skeleton Coast	3	**75**	**8**	**13**	**3**	**1**	**0**	100.0	**409**	**79**	**6**	**4**	**1**	**1**	**6**	**18**	**2**	**0**	**6**	**61**	**0**	100.0	**48**
(dunes)		*2*	*2*	*3*	*1*	*0*	*0*		*79*	*11*	*0*	*2*	*2*	*1*	*2*	*8*	*1*	*0*	*2*	*3*	*0*		*3*
Moçâmedes Desert	1	78	4	12	5	0	1	100.0	383	64	4	4	0	1	11	24	3	0	13	43	0	100.0	50
Swakop River	2	**69**	**13**	**16**	**0**	**1**	**0**	100.0	**466**	**396**	**3**	**7**	**3**	**3**	**4**	**22**	**15**	**4**	**27**	**13**	**0**	100.0	51
		5	*3*	*3*	*0*	*0*	*0*		*37*	*82*	*0*	*3*	*3*	*2*	*2*	*4*	*8*	*3*	*4*	*1*	*1*		
Omaruru River	1	58	16	25	1	1	1	100.0	443	182	1	24	5	11	11	19	0	3	18	7	1	100.0	50
Ugab+Huab Rivers	3	**57**	**17**	**17**	**3**	**3**	**3**	100.0	**315**	**200**	**4**	**4**	**1**	**3**	**8**	**10**	**0**	**1**	**23**	**49**	**1**	100.0	40
		10	*10*	*1*	*4*	*2*	*2*		*57*	*188*	*2*	*4*	*1*	*0*	*5*	*2*	*0*	*1*	*0*	*3*	*0*		
Etendeka Plateau	3	**1**	**0**	**12**	**88**	**0**	**0**	100.0	n.d.	**0**	**24**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**99**	**0**	100.0	**39**
(R.Koigab+R.Axab)		*1*	*0*	*4*	*5*	*0*	*0*			*0*	*7*	*0*	*0*	*0*	*1*	*0*	*0*	*0*	*0*	*1*	*0*		*2*
Koigab+Uniab mouths	3	**65**	**5**	**16**	**14**	**1**	**0**	100.0	n.d.	**9**	**9**	**1**	**1**	**2**	**7**	**17**	**2**	**0**	**6**	**63**	**0**	100.0	n.d.
		7	*1*	*1*	*5*	*0*	*0*			*4*	*5*	*1*	*1*	*1*	*0*	*7*	*2*	*0*	*3*	*2*	*0*		
Kaoko Belt	3	**64**	**16**	**12**	**1**	**2**	**5**	100.0	**360**	**340**	**10**	**2**	**0**	**0**	**45**	**2**	**0**	**1**	**50**	**0**	**0**	100.0	44
(R.Hoarusib+R.Marienfluss)		*0*	*0*	*3*	*1*	*3*	*1*		*108*	*136*	*12*	*1*	*0*	*0*	*31*	*2*	*0*	*1*	*34*	*0*	*1*		
Kunene River	3	**70**	**15**	**12**	**1**	**1**	**1**	100.0	**273**	**63**	**2**	**3**	**3**	**0**	**30**	**1**	**0**	**2**	**49**	**11**	**2**	100.0	**51**
		13	*4*	*13*	*0*	*1*	*1*		*32*	*79*	*2*	*3*	*2*	*0*	*4*	*1*	*0*	*2*	*8*	*16*	*1*		*0*

Highlights

- Quantitative study of sand provenance, mixing and dispersal in hyperarid Namibia
- Compositional changes monitored during high-energy littoral and eolian transport
- Sediment budgets assessed with mineralogical, geochemical and geochronological data
- Orange sand travels ≥1750 km to accumulate in Skeleton Coast and Moçâmedes dunes
- Diamond placers in northern coastal Namibia are derived from the Orange River