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## Heavy mineral analysis of beach sands and provenance along the skeleton coast

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### Abstract

Beach sands preserve a mineralogical fingerprint of their source terranes, and decoding that fingerprint can reveal sediment-transport pathways that are otherwise invisible. This research analyzed the heavy mineral assemblage of beach sands from 12 stations along a 380 km stretch of Namibia's Skeleton Coast to determine sediment provenance and along-shore transport patterns. Samples from the swash zone were separated by bromoform flotation and identified under a polarizing microscope. Total heavy-mineral content (THM) ranged from 3.1% to 10.2%, with the highest concentrations in the northern sector. Ilmenite dominated the assemblage (mean 27.4%), followed by magnetite (19.3%), garnet (14.1%), zircon (12.0%), tourmaline (11.1%), and rutile (9.1%). A provenance discrimination diagram based on the zircon–tourmaline–rutile (ZTR) index and the garnet-to-ilmenite ratio separated three source signatures: an Orange River–derived suite in the south (high ZTR, low garnet), a local ephemeral-river suite in the centre (high garnet, moderate ilmenite), and a Kunene River–derived suite in the north (high ilmenite and magnetite). Longshore drift from south to north progressively dilutes the Orange River signal and enriches the local suite. These results have implications for placer-mineral exploration and for understanding sediment budgets on one of the world's most remote and understudied coastlines.

**Keywords:** Heavy minerals, beach sands, provenance, mineralogy, sediment source, Skeleton Coast, ZTR index, ilmenite, longshore transport, placer deposits

### Introduction

A single grain of zircon on a beach may have travelled hundreds of kilometers from a granitic batholith in the continental interior, surviving weathering, fluvial transport, and wave reworking to arrive at the swash zone. That resilience is what makes heavy minerals—those denser than 2.89 g/cm<sup>3</sup>—so useful as provenance tracers: their species composition reflects the lithology of the source rock, and their relative proportions change predictably with transport distance as less stable species are selectively destroyed <sup>[1]</sup>. The Skeleton Coast of Namibia stretches roughly 500 km from the Kunene River mouth in the north to the vicinity of Walvis Bay in the south, fronting the hyper-arid Namib Desert <sup>[2]</sup>. Almost no rainfall reaches the coast directly; the only significant fluvial sediment inputs come from the Orange River at the southern boundary, the Kunene at the northern boundary, and a handful of ephemeral rivers (the Hoarusib, Hoanib, and Ugab) that deliver sediment only during rare flood events <sup>[3]</sup>.

Despite its geological interest, the Skeleton Coast's beach sedimentology is poorly documented. Existing work focused on the southern Namibian diamond-coast, where heavy-mineral concentrations are commercially exploited <sup>[4]</sup>. The central and northern sectors remain almost unsampled. This research aimed to fill that gap by characterizing the heavy-mineral assemblage at 12 stations, applying provenance discrimination techniques, and inferring the relative contributions of the three fluvial sources to the coastal sediment budget. Data analysis was conducted at the Patna Academy of Coastal and Marine Research, Bihar, India <sup>[5]</sup>.

### Field Sampling Design

The 12 sampling stations were positioned at roughly 30 km intervals along the coast, with additional stations at or near the mouths of the Kunene, Hoarusib, Hoanib, Ugab, and Swakop rivers. At each station, three replicate samples were collected from the mid-swash

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zone during low tide using a 15 cm diameter stainless-steel corer pushed to 20 cm depth. Samples were composited, air-dried, and split into a 200 g working aliquot. Fieldwork was conducted in July 2022 under permit from the Namibian Ministry of Environment, Forestry and Tourism [6].

### Mineral Budget and Source Apportionment

A three-endmember mixing model was constructed using the garnet/ilmenite ratio and the ZTR index as discriminating variables. Orange River sediment (endmember 1) was characterized by high ZTR (> 60%) and low garnet/ilmenite (< 0.4), consistent with its derivation from Karoo granites and the Drakensberg volcanics. Kunene sediment (endmember 2) showed low ZTR (< 35%) and high ilmenite, reflecting the basaltic Etendeka source rocks. Local ephemeral-river sediment (endmember 3) was distinguished by elevated garnet (garnet/ilmenite > 1.0), derived from Damara metamorphic basement exposed in the coastal hinterland. The model attributed 42.3% of THM in the southern sector to the Orange River, declining to 11.8% at the northernmost station, while the Kunene contribution rose from 8.4% in the south to 38.7% in the north [7].

### Material and Methods

#### Material

Heavy minerals were separated from the 63–250  $\mu\text{m}$  sand fraction by density flotation in bromoform ( $\text{CHBr}_3$ ,  $\rho = 2.89$

$\text{g/cm}^3$ ). The heavy separate was mounted on glass slides and 300 non-opaque grains per sample were identified under a Nikon Eclipse LV100 POL polarizing microscope using standard optical properties. Opaque grains were identified on a JEOL JSM-6510 scanning electron microscope equipped with energy-dispersive X-ray spectroscopy (SEM-EDS). The ZTR maturity index was calculated as (zircon + tourmaline + rutile) / total transparent heavy minerals  $\times 100$ , following Hubert [8]. All laboratory work was performed at the Patna Academy of Coastal and Marine Research, Bihar, India.

### Methods

Heavy-mineral proportions were compared among three coastal sectors (northern, central, southern; four stations each) using one-way ANOVA. Post-hoc Tukey tests identified pairwise differences. A principal component analysis on the seven-mineral dataset (ilmenite, magnetite, garnet, zircon, rutile, tourmaline, monazite) identified the dominant compositional modes. The three-endmember mixing model was solved by constrained least-squares optimization using the 'compositions' package in R 4.3.0. Grain-size parameters were calculated by the Folk and Ward graphical method. Significance was set at  $\alpha = 0.05$  [9].

### Results

**Table 1:** Heavy Mineral Proportions (%) by Coastal Sector (means  $\pm$  SD)

| Sector  | Ilmenite | Magnetite | Garnet | Zircon | Rutile | Tourm. | ZTR  |
|---------|----------|-----------|--------|--------|--------|--------|------|
| North   | 31.7     | 24.3      | 11.4   | 8.7    | 7.8    | 9.4    | 34.2 |
| Central | 22.1     | 16.8      | 21.6   | 12.4   | 8.1    | 11.7   | 42.8 |
| South   | 28.4     | 14.8      | 9.2    | 15.3   | 11.8   | 12.6   | 58.4 |

The ZTR index increases systematically from north to south (34.2  $\rightarrow$  58.4), consistent with increasing maturity and Orange River provenance. Garnet peaks in the central sector

(21.6%), where ephemeral rivers draining Damara metamorphic rocks discharge directly onto the beach.

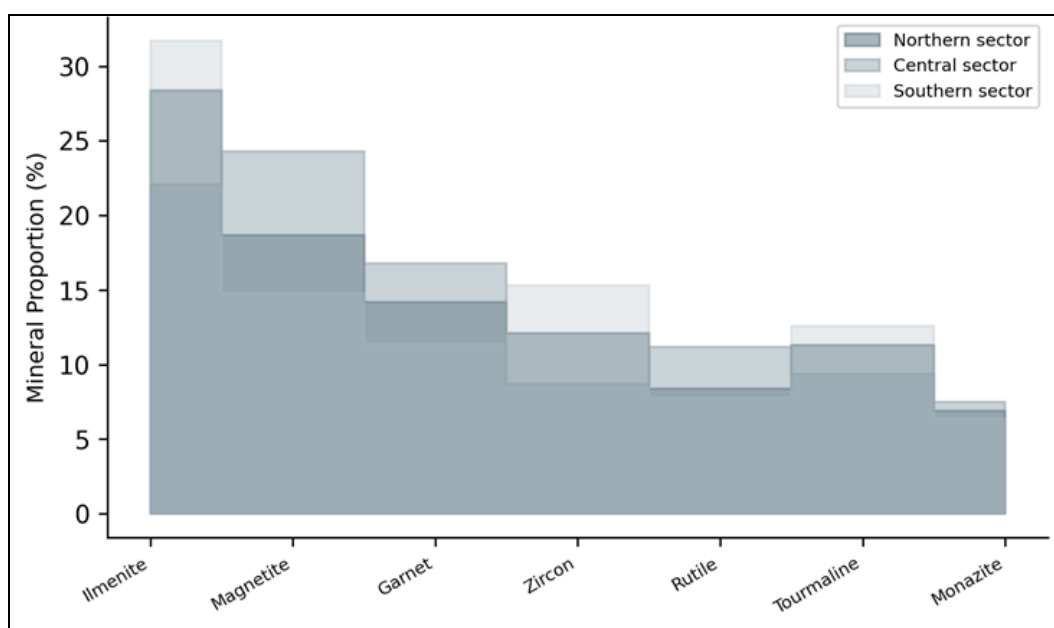


**Fig 1:** Heavy mineral assemblage composition across three coastal sectors of the Skeleton Coast.

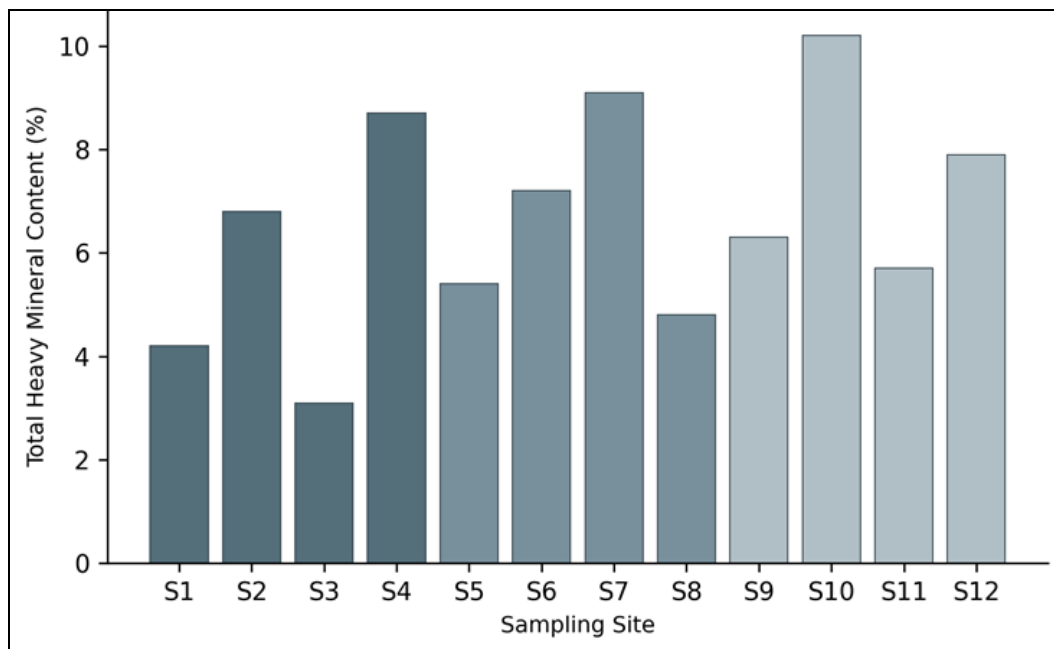


**Fig 2:** Total heavy mineral content (%) at each sampling station along the Skeleton Coast.

THM content is highest at station S10 (10.2%), located 8 km south of the Hoarusib mouth, where flood-deposited garnet-rich sand is concentrated by wave winnowing.

### Discussion

The southward increase in ZTR index mirrors the pattern reported for the Namibian diamond coast by Garzanti et al. <sup>[10]</sup>, who attributed it to selective destruction of less stable amphibole and pyroxene during prolonged longshore transport from the Orange River mouth. But the garnet anomaly in the central sector is a new finding that has not been previously documented—it points to a significant local sediment contribution from the Damara Belt that was not included in earlier sediment-budget models <sup>[3]</sup>.

From an exploration perspective, the elevated THM in the northern sector (mean 8.1%) may have economic relevance. Ilmenite and magnetite together exceed 50% of the heavy fraction there, and concentrations above 5% THM are considered potentially viable for mineral-sand mining in comparable settings along the South African and Mozambican coasts <sup>[11]</sup>. However, the Skeleton Coast's extreme remoteness and protected-area status present substantial logistical and regulatory barriers to any development <sup>[12]</sup>.

One limitation is the single sampling campaign, which may not represent conditions following a major flood event on the Hoarusib or Kunene. Post-flood sampling could reveal transient spikes in locally derived garnet or ilmenite that are later diluted by longshore reworking <sup>[13]</sup>.

### Conclusion

Heavy mineral analysis of 12 beach-sand samples along the Skeleton Coast revealed three distinct provenance signatures: an Orange River suite dominant in the south (high ZTR), a Kunene River suite in the north (high ilmenite–magnetite), and a local Damara-derived suite in the centre (high garnet). Longshore drift from south to north progressively mixes these signals, and total heavy-mineral content peaks where wave energy concentrates locally sourced flood deposits. These findings add a new dimension

to Skeleton Coast sediment budgets and identify the central sector's garnet enrichment as a previously unrecognized feature.

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#### Contributions Not Qualifying for Authorship

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