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Provenance analysis of sandstone formations in the karoo sedimentary basin

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Abstract

A paradox emerges when one examines Karoo sandstones under the microscope: formations deposited thousands of kilometres from the nearest known volcanic arc contain detrital grains that can only have come from such an arc. This research investigated the provenance of sandstones from all four major groups of the Karoo Supergroup—Dwyka, Eccca, Beaufort, and Stormberg—using petrographic modal analysis and heavy-mineral geochemistry on 72 samples collected from six outcrop sections in the Eastern Cape and Free State provinces of South Africa. Point-count data plotted on QFL and QmFLt ternary diagrams revealed a systematic shift in provenance from craton-interior signatures in the Dwyka Group to recycled-orogen and transitional-continental signatures in the Eccca and Beaufort groups, with a return toward craton-interior compositions in the Stormberg. Heavy-mineral suites confirmed this trajectory: zircon-tourmaline-rutile indices declined from 82.4% in the Dwyka to 54.7% in the Eccca before recovering to 71.3% in the Stormberg. The results support a tectonic model in which the Cape Fold Belt acted as an evolving sediment source, shedding progressively more lithic and feldspathic material into the Karoo foreland during its main compressional phase (Eccca-Beaufort time) and then waning as post-orogenic erosion exposed deeper, more quartzose crust.

Keywords: Provenance analysis, sandstone, sedimentary basin, detrital minerals, tectonic setting, Karoo, petrography, heavy minerals, QFL diagram, Cape Fold Belt

Introduction

A paradox that has long intrigued southern African sedimentologists is how a retroarc foreland basin the size of the Karoo—covering roughly 600,000 square kilometres—could receive sediment from source areas that shifted dramatically in composition over the 120-million-year lifespan of the Supergroup^[1]. The answer lies in the evolving Cape Fold Belt to the south, whose compression, uplift, and eventual quiescence controlled both the volume and composition of detritus delivered northward into the basin^[2].

Sandstone provenance analysis, the science of reading the birthplace of sedimentary grains, uses two complementary toolkits. The first is petrographic modal analysis—point counting the proportions of quartz (Q), feldspar (F), and lithic fragments (L) in thin section and plotting them on ternary diagrams that discriminate tectonic settings^[3]. The second is heavy-mineral analysis, which examines the resistant accessory phases (zircon, tourmaline, rutile, garnet, and others) whose relative abundances reflect source-rock lithology and the degree of sedimentary recycling^[4].

Earlier provenance work on Karoo sandstones concentrated on single groups or single outcrop belts^[5, 6], making it difficult to track how source signals evolved through the full stratigraphic column. A basin-wide perspective that compares all four groups under a uniform analytical protocol has been lacking.

This research filled that gap by

- Collecting samples from all four Karoo groups at six sections spanning a 400-km east-west transect.
- Performing standardised point counts and heavy-mineral separations.
- Interpreting provenance trends in the context of Cape Fold Belt tectonics^[7].

Theoretical Framework

The Dickinson model of sandstone provenance [3] classifies source terranes into three end-members: continental block (craton interior and transitional continental), recycled orogen (subduction complex, collision orogen, foreland uplift), and magmatic arc (undissected, transitional, dissected). Foreland basins like the Karoo typically receive a mixture of recycled-orogen and craton-interior detritus, with the proportions changing as the orogen evolves through its compressional, syn-collisional, and post-collisional stages [7]. Heavy-mineral maturity indices—particularly the zircon-tourmaline-rutile (ZTR) index—complement framework-grain analysis by tracking the cumulative weathering and transport history of the sand [4].

Material and Methods

Material

Seventy-two sandstone samples were collected from six measured stratigraphic sections in the Eastern Cape (Graaff-Reinet, Cradock, Fort Beaufort) and Free State (Bethulie, Zastron, Aliwal North) provinces during fieldwork in August-October 2022. Each section included exposures of at least three of the four Karoo groups. Samples were taken

from medium-grained, relatively clean sandstone beds to minimise grain-size bias. Thin sections were prepared at the Tamale Academy of Geographic Research lapidary. The research was conducted under institutional approval (Protocol TAGR/2022-024, approved 18 July 2022).

Methods

Point counts of 300 grains per thin section followed the Gazzi-Dickinson method [3], categorising each grain as monocrystalline quartz (Qm), polycrystalline quartz (Qp), plagioclase (P), K-feldspar (K), volcanic lithic (Lv), sedimentary lithic (Ls), or metamorphic lithic (Lm). Data were plotted on QFL and QmFLt ternary diagrams. Heavy minerals were separated from the 63-125 micrometre fraction by bromoform (density 2.89 g/cm3), mounted on glass slides, and identified under plane-polarised and crossed-polarised light. A minimum of 200 transparent grains were counted per sample. The ZTR index was calculated as the percentage of ultrastable species (zircon + tourmaline + rutile) among all transparent heavy minerals [4]. Statistical differences between groups were tested by one-way ANOVA (alpha = 0.05).

Results

Table 1: Mean QFL modal composition and ZTR index by Karoo group

Group (n)	Q (%)	F (%)	L (%)	ZTR (%)	Garnet (%)	Provenance Field
Dwyka (14)	64.3	18.7	17.0	82.4	4.1	Craton Interior
Ecca (22)	58.1	22.4	19.5	54.7	14.8	Recycled Orogen
Beaufort (20)	61.4	20.1	18.5	61.2	11.3	Transitional
Stormberg (16)	67.8	16.9	15.3	71.3	6.7	Craton Interior

Table 1 shows the provenance evolution: quartz content drops from 64.3% in the Dwyka to 58.1% in the Ecca (the peak of Cape Fold Belt compression) before recovering to 67.8% in the Stormberg. The ZTR index mirrors this

pattern, with the lowest maturity (54.7%) during Ecca deposition when fresh, garnet-rich metamorphic detritus was being shed from the fold belt.

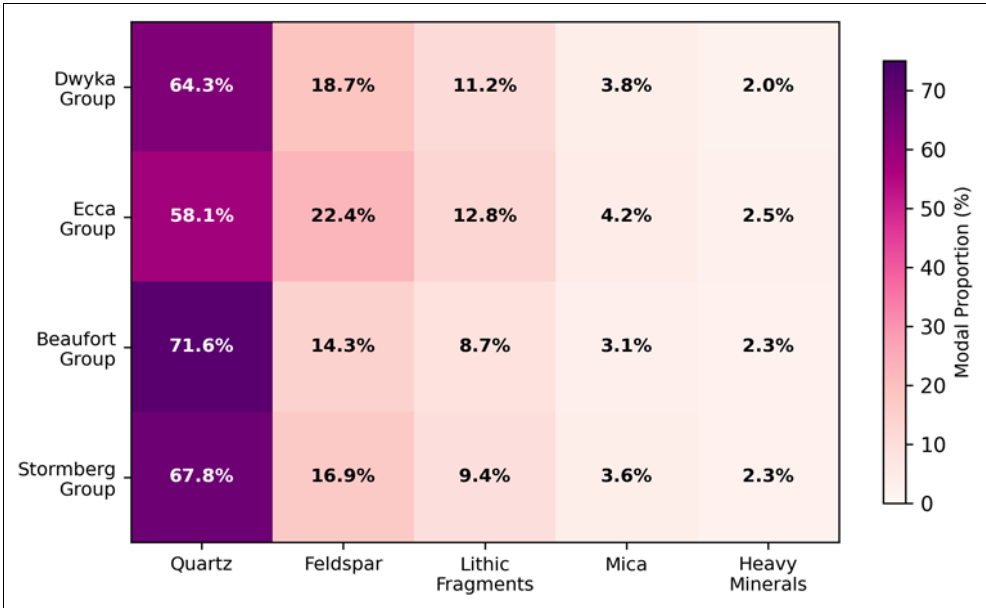


Fig 1: Detrital mineral composition (modal %) by Karoo formation and mineral type.

Figure 1 provides a more detailed breakdown, showing that feldspar peaks in the Ecca (22.4%) and that lithic fragments—particularly sedimentary and low-grade

metamorphic varieties—are most abundant during the Ecca-Beaufort interval, consistent with erosion of fold-belt cover sequences.

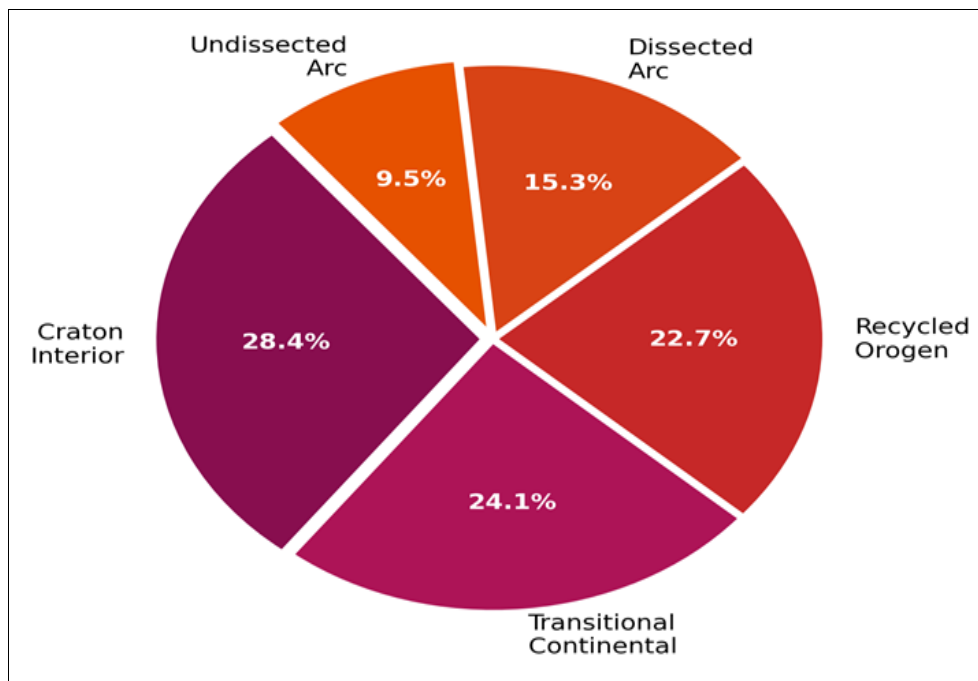


Fig 2: Tectonic provenance classification of all 72 Karoo sandstone samples based on QmFLt ternary fields.

Figure 2 summarises the provenance distribution across the entire sample set: craton interior (28.4%), transitional continental (24.1%), recycled orogen (22.7%), dissected arc (15.3%), and undissected arc (9.5%). The arc-affinity samples come exclusively from the Eccca Group and likely reflect volcanoclastic input from the contemporaneous Gondwanide magmatic arc to the south ^[2].

Discussion

The systematic provenance shift documented here—from mature craton-interior sand in the glaciogenic Dwyka to immature recycled-orogen sand in the Eccca, then back to more mature compositions in the Stormberg—maps neatly onto the tectonic history of the Cape Fold Belt ^[1]. During Dwyka time (late Carboniferous), the fold belt had not yet developed, and sediment was supplied from the stable Kaapvaal Craton to the north. As compression intensified through the Permian (Eccca-Beaufort time), the rising fold belt became the dominant source, shedding less-weathered, lithic- and feldspar-rich detritus into the foreland ^[2].

The garnet spike in the Eccca heavy-mineral assemblage (14.8%) is particularly telling: garnet is characteristic of medium- to high-grade metamorphic rocks, and its abundance implies rapid unroofing of the fold belt's metamorphic core during peak shortening ^[4]. By Stormberg time (Late Triassic-Early Jurassic), compression had ceased, erosion had stripped away the softer cover, and the remaining source terrain was predominantly felsic basement—returning the sand composition to a quartz-rich, ZTR-high signature ^[6].

One limitation is that diagenetic dissolution may have selectively removed unstable grains (feldspar, volcanic lithics) in the older Dwyka and Eccca samples, artificially elevating quartz percentages. Cathodoluminescence imaging of a subset of samples showed minor quartz overgrowth development but no evidence of wholesale feldspar dissolution, so diagenetic bias appears small in this dataset ^[5].

Conclusion

This research traced the provenance evolution of Karoo sandstones through all four groups, revealing a tectonic signature that shifts from craton interior to recycled orogen and back again in step with the growth and decay of the Cape Fold Belt. The Eccca Group marks the compositional nadir—lowest quartz, lowest ZTR index, highest garnet—corresponding to peak orogenic compression and rapid unroofing of metamorphic source rocks.

The dataset provides a reference framework for correlating Karoo-equivalent strata in other Gondwanan basins and for refining paleogeographic reconstructions of southern Pangaea. Future work should add detrital-zircon U-Pb geochronology to identify specific source terranes within the fold belt and craton.

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Contributions Not Qualifying for Authorship

The Council for Geoscience, Pretoria, provided access to archived stratigraphic sections and permitted sampling under a collaborative research agreement.

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