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The Segmented Zambezi Sedimentary System from Source to Sink: 2. Geochemistry, Clay Minerals, and Detrital Geochronology

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Abstract :

Elemental geochemistry, Nd isotopes, clay minerals, and U-Pb zircon ages integrated by petrographic and heavy-mineral data offer a multi-proxy panorama of mud and sand composition across the Zambezi sediment-routing system. Detrital-zircon geochronology highlights the four major episodes of crustal growth in southern Africa: Irumide ages predominate over Pan-African, Eburnean, and Neoarchean ages. Smectite, dominant in mud generated from Karoo basalts or in the equatorial/winter-dry climate of Mozambican lowlands, prevails over illite and kaolinite. Elemental geochemistry reflects quartz addition by recycling (Uppermost Zambezi), supply from Karoo basalts (Upper Zambezi), and first-cycle provenance from Precambrian basements (Lower Zambezi). Mildly negative ϵ_{Nd} for sediments derived from mafic granulites, gabbros, and basalts, and ϵ_{Nd} values are most negative for sand derived from cratonic gneisses. Intrasample variability among cohesive mud, very coarse silt, and sand is principally caused by the concentration of Nd-rich monazite in the fine tail of the size distribution. The settling-equivalence effect also explains deviations from the theoretical relationship between ϵ_{Nd} and TNd,DM model ages, suggesting that monazite carries a more negative ϵ_{Nd} signal than less dense and less durable heavy minerals. Elemental geochemistry and Nd isotopes reveal that the Mazowe-Luenha river system contributes most of the sediment reaching the Zambezi Delta today, with minor supply by the Shire River. Sediment yields and erosion rates are lower by an order of magnitude on the low-relief Kalahari Plateau than in rugged Precambrian terranes. On the Plateau, mineralogical and geochemical indices testify to extensive breakdown of feldspars and garnet unjustified by the presently dry climate. Detrital kaolinite is recycled by incision of Cretaceous- Cenozoic paleosols even in the wetter lower catchment, where inefficient hydrolysis is testified by abundant fresh feldspars and undepleted Ca and Na. Mud geochemistry and surficial corrosion of ferromagnesian minerals indicate that, at present, weathering increases only slightly downstream the Zambezi River.

Keywords : Provenance analysis, Sedimentary geochemistry, δ Al indices, Nd isotopes, U-Pb ages, Detrital zircons, Sediment fluxes, Erosion rates, Kaolinite recycling, Chemical weathering.

“The man who drinks Zambezi waters must always return to drink again”
 [Old Matabele saying in *The Leopard Hunts in Darkness*, Wilbur Smith]

Introduction

The Zambezi, the fourth longest river in Africa and the largest draining into the Indian Ocean (Fig. 1; Moore et al. 2007), underwent a still incompletely understood multistep evolution through time, influenced by rifting events that punctuated the ~280-Ma-long break-up history of Gondwana (Key et al. 2015). For large tracts the river flows along Permian-Triassic rift troughs and its general eastward slope originated from domal uplift associated with the Early Cretaceous rifting of the South Atlantic in the west (Cox 1989; Moore and Blenkinsop 2002).

The modern drainage developed through the Neogene as a consequence of surface uplift of the broad Kalahari Plateau and southwestward propagation of the East African Rift, which created the tectonic depressions occupied by Lake Malawi in the east and by the Okavango inland delta in the west (Ebinger and Scholz 2012). After diverse events of river capture and drainage reversal, a youthful lower course in Mozambique eroded backwards to eventually connect with the upper course on the Kalahari Plateau, forcing it to plunge into Victoria Falls and the basaltic gorges downstream (Wellington 1955; Moore and Larkin 2001). The drainage basin continued to expand in the Quaternary, with the capture of the Angolan Kwando tributary and the presently incipient capture of the large Okavango River as well (Gumbrecht et al. 2001).

In the Anthropocene, the course of the Zambezi ceased to be natural and was rigidly segmented by the construction of the great dams that created Lake Kariba (1958) and Lake Cahora Bassa (1974). Because the sediment-routing system (Hinderer 2012; Allen 2017) is strictly partitioned by these two major reservoirs, it is here convenient to distinguish four reaches: the Uppermost Zambezi headwaters as far as the Kwando confluence, the Upper Zambezi that includes Victoria Falls and the gorges as

far as Lake Kariba, the Middle Zambezi between the two reservoirs, and the Lower Zambezi downstream of Lake Cahora Bassa (Fig. 1).

This study integrates the petrographic and heavy-mineral data illustrated and discussed in the companion paper (Garzanti et al. 2021a) with new data on elemental geochemistry, Nd-isotope geochemistry, clay mineralogy, and detrital-zircon geochronology from the same sample set. The two articles in combination provide a multi-proxy characterization of sediment composition in the diverse tracts of the large Zambezi catchment from the Zambian headwaters to the Mozambican coast. Our main aims are to: a) refine provenance diagnoses based on diverse compositional parameters from both mud and sand fractions of the sediment flux; b) unravel the relative effects of source-rock lithology, recycling, hydraulic sorting, and chemical weathering on the mineralogical and chemical composition of mud and sand generated in humid subequatorial to dry tropical climate; c) infer sediment yields and erosion patterns in diverse parts of the large basin; d) evaluate the relative importance of chemical weathering as occurring in present climatic conditions *versus* mineralogical and chemical signatures of weathering inherited from past climatic conditions *via* recycling of detrital components.

Geology

The Zimbabwe Craton represents the northern part of Archean southern Africa (Fig. 2A). A central terrane flanked by two distinct greenstone belts includes gneisses non-conformably overlain by volcanic rocks and conglomerates. The craton was stabilized between 2.7 and 2.6 Ga and eventually sealed by the Great Dyke swarm at 2575 Ma (Kusky 1998; Jelsma and Dirks 2002; Söderlund et al. 2010).

Tectonic activity continued through the Paleoproterozoic, when the Proto-Kalahari Craton formed during the major Orosirian episode of crustal growth, and into the Mesoproterozoic, at the end of which the Kalahari Craton was eventually assembled (Hanson et al. 2006; Jacobs et al. 2008). Orosirian orogens include the Ubendian-Usagaran Belts along the southern margin of the Tanzania

50 Craton, and the Magondi Belt, exposing arc-related volcano-sedimentary and plutonic rocks
 51 metamorphosed at amphibolite facies along the northwestern margin of the Zimbabwe Craton
 52 ([Majaule et al. 2001](#); [Master et al. 2010](#)). The Angola Block far to the west represents instead the
 53 southern part of the Congo Craton. It comprises a Central Zone in the east, a Central Eburnean Zone,
 54 and the Lubango Zone extending southwards into Namibia, which recorded several distinct magmatic
 55 events between 2.0 and 1.77 Ga ([De Carvalho et al. 2000](#); [McCourt et al. 2013](#); [Jelsma et al. 2018](#)).

56 The next major episode of crustal growth is documented by the Irumide Belt extending from
 57 southern Zambia to Malawi. The external nappes exposed to the north of the Luangwa Rift include a
 58 2.0-1.9 Ga gneissic basement overlain by quartzite, schist, and minor carbonate deposited around
 59 1.85 Ga (Muva Supergroup). Granitoid suites were emplaced at 1.65-1.52 Ga, 1.36-1.33 Ga, and 1.05-
 60 0.95 Ga ([De Waele et al. 2003](#)). Regional metamorphism increasing southeastwards from greenschist
 61 facies to upper amphibolite facies took place at 1.05-1.02 Ga ([De Waele et al. 2006, 2009](#)). The high-
 62 grade internal zone is exposed to the north of the Lower Zambezi Valley between the Luangwa and
 63 Shire Rivers (Southern Irumide Province; [Alessio et al. 2019](#)) and includes the Tete gabbro-
 64 anorthosite Complex (~1.05 Ga; [Westerhof et al. 2008](#)). The Choma–Kalomo Block in southwestern
 65 Zambia consists of crystalline basement covered by amphibolite-facies paragneiss and schist yielding
 66 zircon grains of Paleoproterozoic age, intruded by two generations of Mesoproterozoic granitoid
 67 plutons (1.37 and 1.18 Ga; [Bulambo et al. 2006](#)) and documenting a thermal event between 1.02 and
 68 0.98 Ma ([Glynn et al. 2017](#)).

69 The Kalahari Craton of southern Africa was eventually welded to the Congo Craton during the
 70 major Neoproterozoic Pan-African orogeny, testified by the Damara–Lufilian–Zambezi Belt
 71 stretching from coastal Namibia to Mozambique ([Frimmel et al. 2011](#); [Fritz et al. 2013](#); [Goscombe](#)
 72 [et al. 2020](#)). The Lufilian Arc consists of Neoproterozoic metasedimentary and metaigneous rocks
 73 hosting Cu-Co-U and Pb-Zn mineralizations ([Kampunzu and Cailteux, 1999](#); [John et al. 2004](#);
 74 [Eglinger et al. 2016](#)). The Zambezi Belt contains a volcano-sedimentary succession deformed under
 75 amphibolite-facies conditions at 0.9-0.8 Ga ([Hanson 2003](#)), whereas eclogite-facies metamorphism

76 dated at 592 Ma constrains the timing of subduction and basin closure ([John et al. 2003](#)) with thrust
77 emplacement dated as 550-530 Ma ([Hargrove et al. 2003](#)).

78 The Gondwana supercontinent, assembled during the Pan-African Orogeny, started to be
79 disrupted towards the close of the Paleozoic, when Karoo sediments began to accumulate in several
80 depocenters across southern Africa. Karoo basins include the elongated Gwembe and Luangwa
81 troughs that control the drainage of the Middle Zambezi and Luangwa Rivers ([Nugent 1990](#)). The
82 several km-thick Karoo Supergroup begins with Upper Carboniferous to lowermost Permian
83 diamictite, followed by Permian to Middle Triassic turbidite and coal-bearing fluvio-deltaic strata.
84 Permian sandstones contain andesitic-dacitic volcanic detritus ([Johnson 1991](#)) and interlayered tuffs
85 yielding ages mainly between 270 and 260 Ma ([Lanci et al. 2013](#); [McKay et al. 2016](#)). Subsidence in
86 the southern retroarc basin was associated with subduction of paleo-Pacific lithosphere, while
87 transtensional stress propagated southwards from the Neotethyan rift in the north ([Catuneanu et al.](#)
88 [2005](#)). The upper part of the succession consists of Upper Triassic to Lower Jurassic braidplain
89 sandstones, floodplain mudrocks, and aeolian sandstones ([Johnson et al. 1996](#)). Karoo sedimentation
90 was terminated by flood-basalt eruptions recorded throughout southern Africa around 183 Ma
91 ([Svensen et al. 2012](#); [Greber et al. 2020](#)).

92 In the Early Cretaceous, opening of the Indian Ocean led to formation of sedimentary basins and
93 extensive volcanism in the Mozambique Channel. In the Cenozoic, fluvial and lacustrine sediments
94 including basal gravel and sand with calcrete were deposited inland in the Kalahari Basin, hosting the
95 largest continuous sand sea on Earth where repeated phases of eolian deposition took place through
96 the Quaternary ([Haddon and McCarthy 2005](#); [Burrough et al. 2019](#)). Southwestward propagation of
97 the East African rift in the late Neogene ([Daly et al. 2020](#)) eventually reached the Kalahari region,
98 where fault-related subsidence in the Okavango Rift is exerting a major control on drainage patterns
99 ([McCarthy et al. 2002](#); [Vainer et al. 2021](#)).

100 **Geomorphology and River Drainage**

101

102 *Climate.* Southern Africa, with its largely rural population dependent on rain-fed subsistence
 103 agriculture, is particularly vulnerable to climate variability and extreme events. These include severe
 104 droughts affecting much of Zambia, Malawi, Zimbabwe, or northern South Africa, alternating with
 105 devastating floods such as those periodically striking Mozambique. Cyclones occur in the wet season,
 106 and for the first time in 2019 two cyclones caused floods and destruction in the same year (Siwedza
 107 et al. 2021). Climate variability has a multitude of forcing factors that interact with each other and
 108 wax and wane in their importance through time (Reason et al. 2006; Howard and Washington 2019).
 109 Overall, rainfall increases from west to east at subtropical latitudes and from south to north at
 110 subequatorial latitudes, the principal sources of humidity being the Indian Ocean in the east and the
 111 Atlantic Ocean in the northwest (Fig. 2B).

112 The African continent divides the tropical high-pressure zone into the Indian Ocean and South
 113 Atlantic anticyclones, particularly during the austral summer when heating of the landmass reaches
 114 maximum. Moisture derived primarily from air masses moving inland from the warm Indian Ocean
 115 is reduced by orographic effects along the eastern escarpment and declines progressively westward
 116 resulting in increasing aridity. Descending, divergent air masses occur throughout the year along the
 117 west coast, where the temperature inversion is reinforced by the northward-flowing Benguela current
 118 and upwelling of cold Antarctic waters offshore. Dominant southwesterly winds are dry, and thus
 119 contribute to the marked westward decrease in rainfall across the subcontinent. A sharp contrast thus
 120 exists between humid coastal Mozambique (maximum annual rainfall 1.5 m) and the Kalahari Plateau
 121 inland, where quasi-stationary anticyclonic conditions prevail (Fig. 2C). Mozambique is
 122 characterized by tropical climate with a wet season from October to March and a dry season from
 123 April to September (average annual rainfall ~0.65 m at Tete).

124 In subequatorial southern Africa, atmospheric circulation is complex. Moist South Atlantic air
 125 moved inland by westerly winds converges with Indian Ocean air along the Congo Air Boundary,
 126 frequently associated with development of pressure lows and widespread rains across the Kalahari
 127 Plateau. Annual rainfall, chiefly associated with the southward shift of the Intertropical Convergence

128 Zone, reaches 1.4 m in Angola during summer ([Jury 2010](#)). In winter, when the Intertropical
 129 Convergence Zone and Congo Air Boundary migrate northward, interior southern Africa remains
 130 generally dry under the influence of the Indian Ocean anticyclone.

131 ***The River System.*** The Zambezi (length 2575 km, basin area $\sim 1.4 \cdot 10^6 \text{ km}^2$) is the largest river of
 132 southern Africa. Sourced in northwesternmost Zambia among low ridges of the Kasai Shield (part of
 133 the Congo Craton), the river traverses unconsolidated Kalahari sands in the Barotse floodplain, a 30-
 134 50 km-wide wetland flooded for several months by Zambezi waters after the rainy season (peak
 135 discharge in April).

136 The Uppermost Zambezi starts to flow more swiftly as it first encounters basaltic bedrock at
 137 Ngonye Falls, and it is next joined by the Kwando River draining the Kalahari Basin in humid Angola.
 138 While entering the Okavango Rift, the Kwando (here named Linyanti and next Chobe) deviates
 139 sharply eastward along the tectonic depression hosting large swamps and once large paleolakes
 140 ([Burrough et al. 2009](#); [Moore et al. 2012](#)). The graben continues eastward into the Machili Flats
 141 drained by the low-gradient Kasaya and Ngwezi Rivers, eastern Zambezi tributaries sourced in the
 142 Lufilian arc and Choma-Kalomo Block, respectively.

143 Downstream of the Kwando confluence, the Upper Zambezi and its local tributaries — including
 144 the Sinde River sourced in the Choma-Kalomo Block — incise into Karoo basaltic lavas and the
 145 gradient steepens forming minor rapids upstream of Victoria Falls. Next, after plunging some 100 m
 146 into the falls, turbulent Upper Zambezi waters design an astonishing zigzag into steep gorges of black
 147 basalt, the result of progressive retreat of the waterfalls during the Quaternary ([Derricourt 1976](#)).
 148 After receiving tributaries draining Karoo lavas overlain by thin Kalahari dune sand (e.g., Masuie and
 149 Matetsi), the Zambezi reaches Lake Kariba shortly downstream of the confluence with the Gwai
 150 River. Sourced in the Zimbabwe Craton, the low-gradient senile upper course of the Gwai River is
 151 incised — as its east-bank tributaries Umguza and Shangani — in Karoo basalt and sedimentary rocks
 152 surrounded by Kalahari dune sand ([Thomas and Shaw 1988](#); [Moore et al. 2009](#)). In the youthful lower
 153 tract, the Gwai cuts steeply across the Dete-Kamativi Inlier of the Paleoproterozoic Magondi Belt

154 (Glynn et al. 2020) and receives the eastern Tinde tributary mainly draining Pan-African molasse
 155 (Goscombe et al. 2020).

156 The Middle Zambezi between Lakes Kariba and Cahora Bassa flows along a Karoo rift trough
 157 formed along the Pan-African (Kuunga) suture zone (Goscombe et al. 2020) and hosting a thick infill
 158 of basalt-capped Permian-Triassic sedimentary rocks overlying Ordovician to Devonian siliciclastic
 159 strata (Nyambe 1999). The major tributaries in this tract are the Kafue and the Luangwa, both from
 160 Zambia. The Kafue, the longest Zambezi tributary (length 1576 km, basin area 154,200 km²), is
 161 sourced in the Lufilian arc, flows across a 240 km-long swampy flat floodplain, and next drops 550
 162 m into a 60-km-long gorge carved in gneiss and metasedimentary rocks of the West Zambezi Belt to
 163 join the Zambezi ~75 km downstream of Lake Kariba. The Luangwa (length 770 km, basin area
 164 151,400 km²) is sourced in the Ubendian Belt and flows for most of its course along a Karoo rift
 165 trough filled with an 8-km-thick Permian-Triassic sedimentary succession (Banks et al. 1995),
 166 separating the external nappes of the Irumide Belt in the north from the high-grade Southern Irumide
 167 Province in the south. After cutting across Southern Irumide granulites, the Luangwa joins the
 168 Zambezi just upstream of Lake Cahora Bassa.

169 The Lower Zambezi in Mozambique receives tributaries from the west (Sangara, Mufa) and north
 170 (Luia, Morrunguze) that largely drain high-grade Southern Irumide rocks. The largest tributary is the
 171 Shire (*chiri* = steep banks), the outlet of Lake Malawi, which drains largely garnet-free mafic
 172 granulites of the Blantyre domain (southern Malawi-Unango Complex) where middle-lower crust at
 173 the southern margin of the Congo Craton underwent high-grade metamorphism at ~920 Ma
 174 (Goscombe et al. 2020). From the west, the Mazowe and Luenha Rivers drain well into the Archean
 175 Zimbabwe Craton in the headwaters. Downstream, the two rivers cut across the polymetamorphic
 176 Mudzi migmatitic gneisses remobilized during the Pan-African orogeny, and next across the
 177 Neoproterozoic Marginal Gneiss. Lowermost-course tributaries include the Sangadze and Zangue
 178 Rivers sourced in the Pan-African Umkondo Belt, comprising greenschist-facies to lower-
 179 amphibolite-facies schists thrust onto the margin of the Zimbabwe Craton and upper-amphibolite-

180 facies to granulite-facies gneisses in the core (Stenian Barue Complex). The northern Minjova
 181 tributary largely drains the Moatize-Minjova Basin filled by coal-bearing Permian-Triassic Karoo
 182 clastic rocks (Fernandes et al. 2015).

183 In the lowermost tract, the Zambezi River flows along the Lower Zambezi graben, originated as
 184 a failed arm of the Middle Jurassic Mozambique Basin rift (Butt and Gould 2018). Zambezi sediments
 185 have built through time the largest continental shelf along the Indian Ocean coast of Africa (Walford
 186 et al. 2005; Ponte et al. 2019). Large sediment volumes, however, are not deposited in front of the
 187 Zambezi mouth but dragged northeastward by longshore currents (Schulz et al. 2011; van der Lubbe
 188 et al. 2014), forming wide beaches as far as Quelimane and beyond (e.g., Praia da Madal; Fig. 1).

189 **The Zambezi in the Anthropocene.** The course of the Zambezi has been profoundly modified
 190 by man since the second half of the last century. The Kariba and Cahora Bassa Dams built on the
 191 mainstem, as well as others built on major tributaries, have substantially altered the hydrological
 192 regime of the Zambezi River and its delta, and disrupted the natural sediment-routing system
 193 efficiently trapping detritus generated upstream (Davies et al. 2000; Beilfuss and dos Santos 2001;
 194 Calamita et al. 2019). Lake Kariba (length 223 km, storage capacity 185 km³) is the world's largest
 195 artificial reservoir, whereas Lake Cahora Bassa (length 292 km, storage capacity 73 km³) is Africa's
 196 fourth-largest (Vörösmarty and Moore 1991).

197 Since Zambia's independence, two big dams have been built also on the Kafue River, at Itezhi-
 198 Tezhi (“slippery rock”) and in the Kafue Gorge. The Itezhi-Tezhi Dam (storage capacity 6 km³,
 199 completed in 1977) closes the gap through a ridge of ~100-m-high hills where the paleo-Kafue —
 200 once flowing southwards towards Lake Makgadikgadi and the Limpopo River — was captured and
 201 started to flow eastward as part of the Zambezi drainage (Thomas and Shaw 1991; Moore and Larkin
 202 2001). Downstream, the river flows sluggishly in the maze of swampy channels and lagoons of the
 203 Kafue Flats and next plunges into the Kafue Gorge, where other dams have been constructed (Upper
 204 Kafue Gorge; storage capacity 0.8 km³, operational since 1973) or are under construction (Lower
 205 Kafue Gorge). Other dams were built (e.g., Nkhula, Tedzani, Kapichira), or are planned, on the Shire

206 River in southern Malawi. Besides human intervention, the Zambezi sediment-routing system is
 207 segmented by natural processes as well, much sediment being retained in large wetlands such as the
 208 Barotse floodplain and Chobe swamps on the Uppermost Zambezi, the Kafue Flats, or the Elephant
 209 Marsh on the Shire River (Bolton 1984; Moore et al. 2007).

210 ***Sediment Fluxes.*** Information on sediment loads transported both before and after the
 211 construction of the big dams is largely missing throughout the Zambezi drainage basin. In the lack of
 212 accurately gauged sediment fluxes, estimates on annual solid transport range widely between 20 and
 213 100 million tons (Hay 1998), with a median value around 50 million tons (Milliman and Meade 1983;
 214 ESIA 2011; Milliman and Farnsworth 2011). These figures correspond to an average annual sediment
 215 yield and erosion rate between 15 and 70 tons/km² and between 0.005 and 0.03 mm (median values
 216 ~35 tons/km² and ~0.01 mm). Based on cosmogenic nuclide data, the annual Uppermost Zambezi
 217 sediment flux was estimated as 5.5±0.6 million tons (Wittmann et al. 2020), corresponding to a
 218 sediment yield and erosion rate of 16±2 tons/km² and 0.006 ±0.001 mm. An annual sediment volume
 219 of only 100,000 m³, ascribed to low topographic gradient and presence of vast wetlands on the
 220 Kalahari Plateau, was estimated at Victoria Falls, whereas nearly half of the sediment flux (22 out of
 221 51 million m³) was considered as generated in the Lower Zambezi catchment (FFEM 2005; van der
 222 Lubbe et al. 2016). After closure of the Kariba and Cahora Bassa Dams, annual sediment supply to
 223 the Zambezi Delta may have been reduced to as low as 0.8 million m³, between 1% and 7% of which
 224 is bedload (Ronco et al. 2010 p.52; ESIA 2011).

225 Uncertain by an order of magnitude are also the estimates of sediment accumulation in Lake
 226 Kariba (between 7 and 70 million tons according to Bolton 1984, but only ~4 million tons according
 227 to Kunz et al. 2011) and Lake Cahora Bassa (between 20 and 200 million tons according to Bolton
 228 1984 and 28.6 million m³ according to Ronco et al. 2010 p.47). Based on sparse data on sediment
 229 concentration, annual sediment yields of 40 and 200 tons/km² were estimated for the Gwai and
 230 Luangwa catchments, corresponding to average erosion rates of 0.015 and 0.075 mm (Bolton 1984).
 231 Similar values were evaluated for minor tributaries in Zambia and Mozambique (200 tons/km²) and

for the Luangwa and the rest of the Middle Zambezi (170-250 tons/km², from sediment volumes of 14.0 and 14.6 million m³ respectively; [Ronco et al. 2010](#) p.47). Very high annual rates of soil loss (up to 2900 tons/km²) are reported from the Shire catchment in southern Malawi ([Mzuza et al. 2019](#))

235
236

Methods

Between 2011 and 2019, 71 sediment samples were collected from active sand bars (57), levees (2) and freshly deposited muds (12) of the Zambezi River and its major tributaries from the source in northwesternmost Zambia to the delta in Mozambique. Full information on sampling sites is provided in [Appendix Table A1](#) and Google Earth™ file [Zambezi2.kmz](#).

Clay and Silt Mineralogy. The mineralogy of six mud samples from the Middle and Lower Zambezi mainstem and tributaries (Kafue, Sangadze, Shire) was determined on both < 32 µm and < 2 µm fractions by X-ray powder-diffraction (XRD) using a PANalytical Aeris equipment with a Cu tube, at 15 kV, 40 mA. The < 32 µm fraction was separated by wet sieving and diffractograms were performed on randomly oriented powder in the range 2-60° (2θ). The < 2 µm fraction, separated by centrifuging according to Stokes' law, was analysed on oriented aggregates after air-drying (2-30°2θ) and solvation with ethylene-glycol and heating at 550°C (2-15°2θ). Mineral proportions were evaluated semi-quantitatively using diagnostic XRD peak areas ([Moore and Reynolds 1997](#); [Kahle et al. 2002](#)). Further technical information is provided in [Dinis et al. \(2020a\)](#). XRD data previously obtained on the < 32 µm fraction of mud samples collected from the Upper Zambezi catchment and main tributaries including the Kwando and the Gwai ([Garzanti et al. 2014a](#); [Setti et al. 2014](#)) were also considered. The mineralogical dataset is provided in [Table 1](#) and [Appendix Table A2](#).

Mud and Sand Geochemistry. Chemical analyses of 51 sediment samples were carried out at Bureau Veritas Mineral Laboratories (Vancouver, Canada) on quartered aliquots of the < 32 µm (18 river muds) and 63-2000 µm fractions (31 river sands) obtained by wet sieving. Two levee silty sands were analysed in bulk. Following a lithium metaborate/tetraborate fusion and nitric acid digestion, major oxides and several minor elements were determined by ICP-ES and trace elements by ICP-MS

(see [Appendix A](#) and <http://acmelab.com> for detailed information on adopted procedures, standards used, and precision for elements of group 4A-4B and codes LF200 and LF300).

Classic multi-element chemical indices used to estimate weathering and calculated using molar proportions of mobile alkali and alkaline-earth metals include the WIP (Weathering Index; [Parker 1970](#)) and the CIA (Chemical Index of Alteration; [Nesbitt and Young 1982](#)). The WIP, however, merely measures the amount of a set of mobile elements that decreases rapidly wherever quartz is added to the sediment, making it an index of quartz recycling more than an index of weathering. Because correcting the CIA for CaO in carbonates introduces uncertainties ([Garzanti and Resentini 2016](#)), in this study we use the CIA* corrected only for CaO in apatite [$\text{CIA}^* = 100 \cdot \text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + (\text{CaO} - 3.33 \times \text{P}_2\text{O}_5) + \text{Na}_2\text{O} + \text{K}_2\text{O})$]. The weathering effect is best detangled from other controls on geochemical composition if mobile elements (Mg, Ca, Na, K, Sr, and Ba) are considered one by one. This can be done by using $\alpha^{\text{Al}}E$ values, defined as $(\text{Al}/E)_{\text{sample}}/(\text{Al}/E)_{\text{standard}}$ ([Garzanti et al. 2013a, 2013b](#)), which compare the concentration of any mobile element E with reference to non-mobile Al in our samples *versus* an appropriately selected standard composition (e.g., the UCC, Upper Continental Crust standard of [Taylor and McLennan 1995](#); [Rudnick and Gao 2003](#)). Aluminium, hosted in a wide range of rock-forming minerals with diverse density, shape, and size including phyllosilicates (concentrated in mud) and feldspars (concentrated in sand) is used as a reference for all elements rather than Ti, Nd, Sm, or Th ([Gaillardet et al. 1999](#)), which are hosted preferentially in ultradense minerals and thus may reach strongly anomalous concentrations owing to hydrodynamic processes. Geochemical data are summarized in [Table 2](#) and provided in full in [Appendix Table A3](#).

Nd-Isotope Geochemistry. Sixteen samples from the Middle and Lower Zambezi catchment were treated using a sequential leaching procedure for quantitative removal of carbonates, Fe-oxide phases, and organic matter ([Bayon et al. 2002](#)). Prior to geochemical analyses, about 80 mg of powdered samples were digested by HF-HCl-HNO₃ mixture (seven < 32 μm fractions, nine 32-63 μm classes, and two bulk samples) or alkaline fusion (fourteen 63-2000 μm fractions). Selected major and trace-element abundances were determined at the Pôle Spectrométrie Océan (PSO) with a

284 Thermo Scientific Element XR sector field ICP-MS, using the Tm addition method (Barrat et al.
 285 1996). Both the accuracy and precision of measured concentrations were assessed by analyzing three
 286 certified reference materials (AN-G, AGV-1, BCR-1).

287 Neodymium isotopes were measured at PSO using a Thermo Scientific Neptune multi-collector
 288 ICP-MS, after Nd purification by conventional ion chromatography. Repeated analyses of a JNdi-1
 289 standard solution gave $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.512114 ± 0.000005 (2σ , $n=12$), in full agreement with the
 290 recommended value of 0.512115 (Tanaka et al. 2000) and corresponding to an external
 291 reproducibility of $\pm 0.09 \text{ } \epsilon$ (2σ). Epsilon Nd values were calculated using the present-day chondritic
 292 (CHUR) value of $^{143}\text{Nd}/^{144}\text{Nd} = 0.512630$ (Bouvier et al. 2008). Neodymium depleted mantle model
 293 ages ($T_{\text{Nd,DM}}$) were calculated following the approach described in De Paolo (1981), using measured
 294 Sm and Nd concentrations ($^{147}\text{Sm}/^{144}\text{Nd} = \text{Sm}/\text{Nd} \times 0.6049$) and present-day depleted mantle values
 295 of $^{143}\text{Nd}/^{144}\text{Nd} = 0.51315$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.2145$. Isotope data, including results previously
 296 obtained on muds from the upper part of the Zambezi catchment (Garzanti et al. 2014a), are
 297 summarized in Table 3. Geochemical data on all size fractions analysed for isotope geochemistry and
 298 isotope-geochemistry data are provided in full in Appendix Tables A4 and A5.

299 **Detrital-Zircon Geochronology.** Detrital zircons were identified by Automated Phase Mapping
 300 (Vermeesch et al. 2017) with a Renishaw inViaTM Raman microscope on the heavy-mineral separates
 301 of 18 samples, concentrated with standard magnetic techniques and directly mounted in epoxy resin
 302 without any operator selection by hand picking. U-Pb zircon ages were determined at the London
 303 Geochronology Centre using an Agilent 7700x LA-ICP-MS (laser ablation-inductively coupled
 304 plasma-mass spectrometry) system, employing a NewWave NWR193 Excimer Laser operated at 10
 305 Hz with a 25 μm spot size and $\sim 2.5 \text{ J}/\text{cm}^2$ fluence. No cathodo-luminescence imaging was done, and
 306 the laser spot was always placed “blindly” in the center of zircon grains in order to treat all samples
 307 equally and avoid bias in intersample comparison (“blind-dating approach” as discussed in Garzanti
 308 et al. 2018). The mass spectrometer data were converted to isotopic ratios using GLITTER 4.4.2
 309 software (Griffin et al. 2008), employing Plešovice zircon (Sláma et al. 2008) as a primary age

standard and GJ-1 ([Jackson et al. 2004](#)) as a secondary age standard. A NIST SRM612 glass was used as a compositional standard for the U and Th concentrations. GLITTER files were post-processed in R using IsoplotR 2.5 ([Vermeesch 2018](#)). Concordia ages were calculated as the maximum likelihood intersection between the concordia line and the error ellipse of $^{207}\text{Pb}/^{235}\text{U}$ and $^{206}\text{Pb}/^{238}\text{U}$ ([Ludwig 1998](#)). The discordance cutoff was set at -5/+15% of the concordia distance ([Vermeesch 2021](#)). The complete geochronological dataset, comprising 2095 concordant ages refined with a ^{208}Pb -based common Pb correction, is provided in [Appendix B](#).

Statistical methods and graphical displays. The relative contribution from each tributary or geological domain to the sediment flux of a trunk river can be quantified with forward mixing models, provided that the compositional signatures of sediment in each potential source are distinct and accurately determined ([Weltje 1997](#); [Garzanti et al. 2012](#)). The forward mixing model calculates a row vector of compositional data as a non-negative linear combination between a matrix of fixed end-member compositions and a row vector of coefficients representing the proportional contribution of each end member to the observation. The accuracy of calculations depends on how distinct and precisely assessed the end-member signatures of each potential source are. Additional information on the method is contained in [Appendix A](#) and [Resentini et al. \(2017\)](#).

Statistical techniques used to illustrate our datasets include the compositional biplot ([Gabriel 1971](#); [Aitchison and Greenacre 2002](#)) and multidimensional scaling (MDS; [Vermeesch 2013](#); [Vermeesch and Garzanti 2015](#)). The compositional biplot (drawn using CoDaPack software by [Comas and Thió-Henestrosa 2011](#)) allows discrimination among multivariate observations (points) while shedding light on the mutual relationships among multiple variables (rays). The length of each ray is proportional to the variance of the corresponding variable; if the angle between two rays is 0° or 180° , then the corresponding variables are perfectly correlated or anticorrelated. MDS analysis produces a map of points in which the distance among samples is approximately proportional to the Kolmogorov-Smirnov dissimilarity of their compositional or chronological signatures. The goodness of fit is evaluated using the “stress” value of the configuration (20 = poor; 10 = fair; 5 = good; [Kruskal](#)

and Wish 1978). The provenance package of Vermeesch et al. (2016) was used to plot MDS maps and U-Pb age distributions as kernel density estimates (KDE).

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339

Data

This section briefly summarizes petrographic and heavy-mineral data (provided in full in Appendix Tables A6 and A7, and illustrated in detail in the companion paper Garzanti et al. 2021a) and presents new data on clay mineralogy (Table 1; Fig. 3), elemental geochemistry for mud and sand samples (Table 2; Fig. 4), REE geochemistry (Fig. 5), Nd-isotope geochemistry (Table 3; Fig. 6), and detrital-zircon geochronology (Table 4; Fig. 7) from the whole Zambezi River sedimentary system.

Five main zircon-age ranges recur among the analysed samples, corresponding to main thermal events of crustal growth across southern Africa (Hanson 2003; Dirks et al. 2009; Andersen et al. 2016, 2018): A) "Karoo" (Triassic-Permian, 253 ± 21 Ma); B) "Pan-African" (Cambrian-Ediacaran, 571 ± 22 Ma, and Tonian, 792 ± 54 Ma); C) "Irumide" (Stenian, 1036 ± 32 Ma); D) "Eburnean" (Orosirian, 1947 ± 70 Ma); and, E) "Limpopo" (late Neoarchean, 2568 ± 47 Ma) (Table 4). A few zircon ages referred to the Ectasian "Kibaran" (~ 1.35 Ga) or Calymmian/Statherian "Lukamfwa" events (~ 1.55 Ga; De Waele et al., 2003) are recorded mainly in the Upper Zambezi catchment and Luangwa sand. The youngest zircon ages (103-121 Ma) were obtained from lowermost Zambezi sands.

The Uppermost Zambezi. Uppermost Zambezi and Kwando sands are pure quartzose. Sands of left Zambian tributaries range from quartz-rich feldspatho-quartzose (Kabombo, Ngwezi) to pure quartzose (Kasaya). Smectite prevails over kaolinite and mica/illite in mud of the Zambezi mainstem, and is dominant in Ngwezi and Kwando muds (Fig. 3).

In Zambezi and Kwando sands, SiO_2 is overwhelming ($> 98\%$) (Fig. 4A) and other elements very low, including Zr (62-114 ppm) and REE (Fig. 5). The CIA^* is ≥ 77 , the $\text{WIP} < 1$, $\alpha^{\text{Al}}\text{Ca} \geq 3$, and $\alpha^{\text{Al}}\text{Na} \sim 4$. Ngwezi sand is less SiO_2 -rich, with higher Al, Ca, Na, K, Rb, Sr, and Ba but very low Mg (Fig. 4B). Kasaya sand has intermediate composition. Chemical indices are $\text{CIA}^* 83$, $\alpha^{\text{Al}}\text{Ca} 4$, $\alpha^{\text{Al}}\text{Na} 21$ for Zambezi mud and $\text{CIA}^* 77 \pm 1$, $\alpha^{\text{Al}}\text{Ca} 2.9 \pm 0.5$, and $\alpha^{\text{Al}}\text{Na} 11 \pm 4$ for Kasaya and Ngwezi muds.

362 Kwando mud has anomalously low $\alpha^{\text{Al}}\text{Ca}$, $\alpha^{\text{Al}}\text{Mg}$, $\alpha^{\text{Al}}\text{Sr}$, and $\alpha^{\text{Al}}\text{Ba}$ (Table 2). The general observed
 363 order of element mobility is $\text{Na} \gg \text{Sr} > \text{Ca} > \text{Mg} \approx \text{K}$ for mud and $\text{Na} \approx \text{Ca} > \text{Sr}$ for sand. In mud
 364 samples, REE patterns normalized to CI carbonaceous chondrites (Barrat et al. 2012) display classical
 365 shapes with higher LREE than HREE fractionation and moderately negative Eu anomaly. Pure
 366 quartzose sands display slightly stronger LREE enrichment, negative Ce anomaly, more strongly
 367 negative Eu anomaly, and low HREE fractionation. The ϵ_{Nd} values vary between -14 and -17 (-15.5
 368 for Uppermost Zambezi mud; Table 3).

369 Ages of zircon grains in Uppermost Zambezi, Kwando, and Kasaya sands display polymodal
 370 spectra, with mostly Cambrian to Stenian ages including a main Irumide and subordinate Pan-African
 371 peaks (Fig. 7). Orosirian ages are common in Uppermost Zambezi and Kwando sands and minor in
 372 Kasaya sand. Kwando sand is distinguished by a Neoproterozoic age cluster, whereas Kasaya sand
 373 yielded several zircon grains with Devonian to Triassic ages.

374 ***The Upper Zambezi.*** Zambezi sand becomes rapidly enriched in basaltic detritus downstream of
 375 Victoria Falls. Bedload sand and levee silty sand upstream of Lake Kariba are, respectively, quartzose
 376 and plagioclase-rich litho-feldspatho-quartzose with mafic volcanic rock fragments and green augite.
 377 Basaltic detritus increases from west to east also in Zambezi tributaries, from quartzose Sinde sand
 378 to lithic-rich litho-quartzose and quartzo-lithic Masuie and Matetsi sands containing common augite.
 379 Smectite predominates over mica/illite and kaolinite in Zambezi mud and is overwhelming in muds
 380 of the Sinde and Matetsi tributaries, which contain kaolinite (Fig. 3).

381 Silica decreases progressively along the Upper Zambezi, with corresponding increase in most
 382 other elements, including Fe, Mg, Ca, Na, Sr (Fig. 4G, 4H) and REE (Fig. 5C), but not Zr, Hf, and
 383 Nb. Chemical indices upstream of Lake Kariba are $\text{CIA}^* 59 \pm 6$, $\alpha^{\text{Al}}\text{Ca} 0.9 \pm 0.3$, $\alpha^{\text{Al}}\text{Na} 3.9 \pm 0.9$ for
 384 mud, $\text{CIA}^* 45$, $\alpha^{\text{Al}}\text{Ca} 0.5$, $\alpha^{\text{Al}}\text{Na} 1.5$ for silty sand, and $\text{CIA}^* 49$, $\alpha^{\text{Al}}\text{Ca} 0.9$, $\alpha^{\text{Al}}\text{Na} 1.2$ for sand.
 385 Tributaries draining progressively larger portions of Karoo basalts display an even sharper trend from
 386 west to east. Masuie and Matetsi sands have much lower SiO_2 than Sinde sand and higher
 387 concentration of all other elements (Fig. 4A). In these rivers, both mud and sand are markedly

388 enriched in Mg, Ca, Sc, Ti, V, Cr, Fe, Mn, Co, Ni, Cu (Fig. 4B), and display regular chondrite-
 389 normalized REE patterns lacking Eu anomaly (Fig. 5A, 5D, and 5G). The ϵ_{Nd} value is around -12 in
 390 Zambezi mud between Victoria Falls and Lake Kariba, and is much less negative for Matetsi (-4) and
 391 Sinde (-5) muds.

392 Sinde sand yielded a zircon-age spectrum with dominant Irumide peak, common Neoproterozoic
 393 ages, and minor Permian-Triassic, Eburnean, and Neoproterozoic ages. Upper Zambezi sand upstream
 394 of Lake Kariba yielded a polymodal spectrum with main Pan-African and Irumide peaks and minor
 395 Orosirian and Neoproterozoic clusters (Fig. 7).

396 Lower Gwai sand is feldspatho-quartzose with biotite and amphibole. Smectite predominates in
 397 upper Gwai and Umguza muds, whereas mica/illite prevails over kaolinite and smectite in mud of the
 398 lower-course Tinde tributary (Fig. 3). Chemical indices are CIA* 73, $\alpha^{\text{Al}}\text{Ca}$ 1.9, $\alpha^{\text{Al}}\text{Na}$ 10 for upper
 399 Gwai mud and CIA* 54, $\alpha^{\text{Al}}\text{Ca}$ 2.9, $\alpha^{\text{Al}}\text{Na}$ 1.4 for lower Gwai sand. Umguza mud is similar as upper
 400 Gwai mud, whereas Umguza sand is much richer in Fe, Mg, Ca, Ti, Mn, Sr, V, Co, Ni, and Cu than
 401 lower Gwai sand (Fig. 4C, 4D). Tinde mud is richer in Si, Na, K, Rb, Ba, YREE, Th, U, Zr, Hf, Nb,
 402 Ta, and poorer in Fe, Mg, Ca, P, Mn, Sc, V, Cr, Co, Ni, and Cu (Table 2). The ϵ_{Nd} value ranges
 403 between -12 and -15 in upper Gwai, Umguza and Tinde muds, but it is strongly negative in Gwai
 404 sand upstream of lake Kariba (-25), which yielded a polymodal zircon-age spectrum with major
 405 Neoproterozoic and Eburnean peaks and minor Irumide and Pan-African peaks (Fig. 7).

406 **The Middle Zambezi.** Between Lakes Kariba and Cahora Bassa, Zambezi sand has the same
 407 feldspar-rich feldspatho-quartzose composition as Kafue sand, with metamorphic rock fragments,
 408 mica, and amphibole. The Luangwa River carries feldspatho-quartzose sand with granitoid to gneissic
 409 rock fragments and amphibole. Smectite predominates over mica/illite and kaolinite in mud of the
 410 Zambezi mainstem, whereas mica/illite predominates over smectite and kaolinite in Kafue mud (Fig.
 411 3).

412 Chemical indices are CIA* 67 ± 3 , $\alpha^{\text{Al}}\text{Ca}$ 2.1 ± 0.6 , $\alpha^{\text{Al}}\text{Na}$ 5.2 ± 0.2 for mud and CIA* 51 ± 3 , $\alpha^{\text{Al}}\text{Ca}$
 413 2.1 ± 1.3 , $\alpha^{\text{Al}}\text{Na}$ 1.6 ± 0.2 for sand. The observed order of element mobility is $\text{Na} > \text{Sr} > \text{Ca} > \text{K} > \text{Ba}$

414 for mud and $\text{Ca} > \text{Na} > \text{Sr}$ for sand. Luangwa sand is higher in SiO_2 , K, Ba, and lower in most other
 415 elements (especially Mg, Ti, and Sc; Fig. 4C). The finer-grained of the two Kafue sand samples is
 416 notably enriched in Zr, Hf, REE, Th, U, Nb, Ta (Table 2). Kafue and Middle Zambezi muds have
 417 virtually identical chemical composition (Fig. 4D, 4H). All ϵ_{Nd} values range between -14 and -18,
 418 reaching -20 only in the 32-63 μm size class of Luangwa sand.

419 The zircon-age spectrum of Kafue sand displays a dominant Irumide peak with a minor Pan-
 420 African cluster and a few Triassic and Paleoproterozoic to Neoproterozoic ages. Luangwa sand is
 421 characterized by a trimodal spectrum with major Irumide, subordinate Pan-African, and minor
 422 Eburnean peaks, and a few Permian ages (Fig. 7).

423 ***The Lower Zambezi.*** In Mozambique, Zambezi sand ranges from quartzo-feldspathic to feldspar-
 424 rich feldspatho-quartzose with biotite, amphibole, and garnet. Most tributaries carry quartzo-
 425 feldspathic sand with amphibole, garnet, clinopyroxene, hypersthene, and epidote. Feldspar (mostly
 426 plagioclase) is twice as abundant as quartz in Shire sand from Malawi. Metabasite grains are common
 427 in Morrunguze sand. Kaolinite, mica/illite, and smectite occur in subequal amount in Zambezi mud
 428 collected at Tete, whereas smectite predominates over mica/illite and kaolinite is subordinate
 429 upstream of the delta (Fig. 3). Sangadze mud consists almost exclusively of smectite, whereas Shire
 430 mud contains mica/illite and kaolinite in subequal proportions (Table 1).

431 Chemical indices are remarkably constant in sediments of the Zambezi mainstem and most of its
 432 main tributaries ($\text{CIA}^* 70 \pm 3$, $\alpha^{\text{Al}} \text{Ca} 2.0 \pm 0.4$, $\alpha^{\text{Al}} \text{Na} 6.0 \pm 2.6$ for mud and $\text{CIA}^* 50.4 \pm 0.5$, $\alpha^{\text{Al}} \text{Ca}$
 433 1.6 ± 0.5 , $\alpha^{\text{Al}} \text{Na} 1.2 \pm 0.2$ for sand) (Table 2). Plagioclase abundance explains why an Eu anomaly is
 434 not shown (Fig. 5H, 5I). The observed order of element mobility is $\text{Na} > \text{Sr} > \text{Ca} > \text{K} > \text{Rb}$ for mud
 435 and $\text{Ca} > \text{Na} > \text{Sr}$ for sand. In all grain-size fractions of Lower Zambezi sediments, ϵ_{Nd} values become
 436 much more negative from Tete to upstream of the delta, where the very-fine-sand sample yielded a
 437 less negative value than the fine-sand sample (Table 3).

438 Sand of the Morrunguze River draining gabbroic rocks of the Tete Complex is low in SiO_2 (52%),
 439 K, and Rb, notably rich in Fe, Mg, Ca, Ti, Mn, Sc, V, Cr, Co, Ni and Cu (Fig. 4E), and yielded the

440 least negative ϵ_{Nd} value (Fig. 6). Mufa sand, enriched in the same elements but to a much lesser extent,
 441 yielded high Zr and Hf concentrations (Table 2) and a more negative ϵ_{Nd} value. Luenha sand is
 442 relatively rich in Zr and Hf, U, Nb, Ta and REE, is the richest in Th (Fig. 4E), displays the steepest
 443 REE patterns with the largest negative Eu anomaly (Fig. 5H, 5K), and is the only sample with negative
 444 loss on ignition (LOI -0.3). Mazowe and Luenha sands have ϵ_{Nd} values of -18 and -19. Shire sand is
 445 highest in Al, Na, Sr, and P, and shows a much less negative ϵ_{Nd} value (Fig. 7). Sangadze sand is the
 446 richest in K, Rb, and Ba, and displays a strongly positive Eu anomaly (Fig. 5H) — reflecting abundant
 447 feldspar and fewer heavy minerals — and a strongly negative ϵ_{Nd} value. Shire mud is low in SiO₂
 448 (42%) and highest in Al, Fe, Sr, Ba, P, Sc, V, and Cu (Fig. 4F). Zambezi mud upstream of the delta
 449 is high in Zr and Hf, REE, Th, U, Nb, Ta, Cr, Mo, W, Co, and Ni (Fig. 4H), and displays a negative
 450 Eu anomaly (Fig. 5I).

451 The U-Pb age spectrum of zircon grains supplied by the Zambezi River to the delta displays a
 452 dominant Irumide peak, with common Neoproterozoic, some Orosirian, and a few Neoarchean and
 453 late Paleozoic ages (Fig. 7). Sangara and Morrunguze zircons show a unimodal Irumide peak, which
 454 is associated with minor Neoproterozoic ages in Mufa sand. Luenha and Mazowe sands yielded nearly
 455 identical bimodal zircon-age spectra with Neoproterozoic and Neoarchean peaks (Table 4). The
 456 spectrum of Shire sand is also bimodal but with Irumide and Pan-African peaks. Pan-African ages
 457 are more common than Irumide ages in Zangue sand (Fig. 7).

458 ***The Northern Zambezi Delta.*** Estuary and beach sand ~100 km north of the Zambezi mouth is
 459 feldspatho-quartzose with amphibole, epidote, and clinopyroxene. The ϵ_{Nd} value of bulk sand ranges
 460 between -13 and -18. The U-Pb zircon-age spectrum displays a dominant Irumide peak with common
 461 Neoproterozoic, some Orosirian and a few Neoarchean and Permian ages, similarly to Lower
 462 Zambezi sand (Fig. 7).

463

464

Provenance Insights from Clay Mineralogy and Sediment Geochemistry

465 Clay mineralogy and sediment geochemistry are largely controlled by factors other than provenance.
 466 If weathering is intense, then they reflect the lithology of source rocks only poorly, which explains
 467 why they have long been used to evaluate weathering rather than provenance (e.g., Nesbitt and Young
 468 1982; Velde and Meunier 2008). However, despite the complexities associated with multiple controls
 469 on sediment composition (Johnsson 1993), clay minerals and elemental and especially isotope
 470 geochemistry do offer complementary information useful to augment the completeness and
 471 robustness of provenance analysis for several reasons (McLennan et al. 1993). Firstly, most other
 472 provenance techniques are best suited to tackle sand and, in the case of detrital geochronology, only
 473 a millesimal fraction of total sand. Geochemistry, instead, can be applied to bulk-sediment samples
 474 of any size fraction from clay to granule. This allows us to investigate almost the entirety of the
 475 sediment flux, including clay and silt that constitute the large majority of the detrital mass transported
 476 in river systems as suspended load (e.g., Hay 1998; Milliman and Farnsworth 2011). The aim of this
 477 section is thus to complement previous considerations based only on sand with inferences derived
 478 independently from the mineralogy and geochemistry of mud.

479 ***Clay Minerals.*** The clay mineralogy of unconsolidated mud depends on weathering processes in
 480 soils but reflects provenance as well, especially in dry climates where illite and chlorite are largely
 481 derived from phyllosilicate-rich metamorphic bedrock whereas smectite is shed by mafic lava (e.g.,
 482 Chamley 1989). Among the studied samples, smectite is the dominant clay mineral ($\geq 87\%$) in mud
 483 transported by the Sinde and Matetsi tributaries of the Upper Zambezi and by the Umguza tributary
 484 of the Gwai River, all partly draining Karoo basalt between southern Zambia and western Zimbabwe.
 485 Smectite, however, is produced in abundance also in regions lacking significant exposures of mafic
 486 rocks (e.g., Kwando catchment) and represents the virtually exclusive clay mineral in mud of the
 487 Sangadze River flowing across Mozambican lowlands, indicating incomplete flushing of mobile ions
 488 in poorly drained low-relief regions (Wilson 1999). Illite is the most abundant clay mineral in mud
 489 of the Kafue and Shire Rivers chiefly draining Proterozoic crystalline basement, and in mud of the
 490 Tinde River draining Neoproterozoic molasse (Fig. 3).

491 ***Sand Geochemistry.*** The piece of provenance information most readily obtained from
 492 geochemical data is the supply from mafic rocks, revealed by high concentrations of ferromagnesian
 493 metals including Mg, Sc, Ti, V, Cr, Mn, Fe, Co, and Ni (Fig. 8; McLennan et al. 1993; von Eynatten
 494 et al. 2003). Among the analysed samples, these elements reach the highest values in Masuie and
 495 Matetsi sands draining Karoo basalts and in Morrunguze sand draining the Tete gabbro-anorthosite
 496 (Fig. 4). Intermediate values for these elements are obtained for the Sinde and Umguza Rivers and
 497 for the Middle Zambezi upstream of Lake Kariba, all draining Karoo basalts more marginally (Table
 498 2). Other samples in the Upper Zambezi catchment have $\text{SiO}_2 > 90\%$, revealing extensive recycling
 499 of pure quartzose Kalahari sand.

500 The virtually identical chemical composition of Kafue and Middle Zambezi muds confirms that
 501 the Kafue is by far the most important source of sediment to the Middle Zambezi between Lake
 502 Kariba and the Luangwa confluence. Slightly above 80% in Kafue and Middle Zambezi sand, SiO_2
 503 raises to nearly 90% in Luangwa sand that contains a greater proportion of detritus recycled from
 504 Karoo siliciclastic strata. In sand of Lower Zambezi tributaries, SiO_2 mostly ranges between 70% and
 505 80%. Composition is closest to the UCC for sand carried by the Lower Zambezi to the Indian Ocean,
 506 confirming its dominantly first-cycle provenance from mid-crustal basement rocks (Garzanti et al.
 507 2021a).

508 Chemical indices provide further clues. Because the addition of quartz grains profoundly affects
 509 the WIP, but not the CIA^* , the CIA^*/WIP ratio can be used to detangle the effects of weathering and
 510 recycling. This ratio reaches ≥ 100 in Uppermost Zambezi and Kwando sands consisting almost
 511 entirely of recycled Kalahari dune sand, decreases to 30 ± 9 in Upper Zambezi sand above and below
 512 Victoria Falls, and next drastically to 3.1 ± 0.7 in Upper Zambezi sand and silty sand upstream of Lake
 513 Kariba. The CIA^*/WIP ratio decreases further to 1.7 ± 0.3 in sand of Middle Zambezi tributaries and
 514 mainstem and is lowest (0.9 ± 0.1) in sand of Lower Zambezi tributaries and mainstem, further
 515 confirming their mostly first-cycle provenance.

516 **Mud Geochemistry.** The geochemical composition of mud samples is more homogeneous. SiO₂
 517 varies between 42% and 54%, being notably higher (68%) only for Tinde mud reflecting recycling
 518 of siliciclastic Pan-African molasse. Kwando mud is markedly enriched in Ca, Sr, Mg, and Ba (Fig.
 519 4B), revealing contribution from calcrete and dolocrete soils (Shaw 2009; McFarlane et al. 2010). Fe,
 520 Ti, Sc, V, Co, and Cu are highest in Sinde mud and Mg in Matetsi mud (Fig. 4A, 4B) largely derived
 521 from Karoo basalt. Lower Zambezi mud upstream of the delta is richest in Cr and Ni (Fig. 4H),
 522 suggesting significant supply from mafic Proterozoic rocks including the Tete gabbro-anorthosite.

523 **Nd-Isotope Geochemistry.** Although the ¹⁴³Nd/¹⁴⁴Nd composition of sediments is controlled by
 524 multiple factors, the provenance signal emerges clearly from data obtained from all analysed size
 525 fractions — cohesive mud (< 32 µm), very coarse silt (32-63 µm), and sand (63-2000 µm) —,
 526 allowing a sharp distinction between sediments derived from mafic igneous rocks and old granitoid
 527 basements (Fig. 9).

528 The least negative ε_{Nd} values characterize Morrunguze sand, largely derived from the upper
 529 Stenian Tete gabbro-anorthosite, and Sinde and Matetsi muds, partly derived from Lower Jurassic
 530 Karoo basalt (Fig. 6). Mildly negative values were also obtained from Mufa sand, partly derived from
 531 Tete mafic rocks, from Shire sediments largely derived from mafic granulites of the Blantyre domain,
 532 and from Lower Zambezi silt collected at Tete and mostly derived from the Southern Irumide
 533 Province (Table 3).

534 At the other extreme, most negative ε_{Nd} values identify Gwai, Mazowe, and Luenha sands
 535 sourced from Archean gneiss of the Zimbabwe Craton. Markedly negative values also characterize
 536 mud in the upper catchments of the Zambezi and Gwai Rivers. Epsilon Nd becomes less negative as
 537 the Upper Zambezi rushes through the basaltic gorges downstream of Victoria Falls, but much more
 538 negative as the Lower Gwai cuts steeply across gneisses of the Dete-Kamativi Inlier. Strongly
 539 negative values also characterize Kafue and Luangwa sediments in the middle catchment, Sangadze
 540 sediment in the lowermost catchment, and Lower Zambezi sediment upstream of the delta.

541 *Intrasample Variability.* The grain-size-controlled intrasample variability of ϵ_{Nd} values is limited
 542 (average standard deviation 1.6 ± 0.9). The sand fraction (63-2000 μm) typically yields a more
 543 negative ϵ_{Nd} than the cohesive mud fraction ($< 32 \mu m$). The most negative ϵ_{Nd} values are obtained
 544 from the 32-63 μm size class of sand samples, representing the fine tail of the size distribution where
 545 ultradense minerals including LREE-rich monazite concentrate because of the settling-equivalence
 546 effect (Rubey, 1933). This is documented by La, Th, and Zr concentrations respectively 7 ± 5 , 9 ± 7 ,
 547 and 6 ± 3 times higher in the 32-63 μm size class than in the 63-2000 μm fraction of sand samples,
 548 with enrichment factors increasing sharply with sample grain size (corr. coeff. 0.91; data from
 549 Appendix Table A4). The opposite holds for the Lower Zambezi silt collected at Tete (Fig. 6), where
 550 the 32-63 μm size class is part of the coarse tail of the size distribution, which is depleted in denser
 551 minerals and yields a less negative ϵ_{Nd} than both $< 32 \mu m$ and 63-2000 μm fractions (Table 3).

552 *Intersample Variability.* Samples collected in nearby localities along the Kafue and Lower
 553 Zambezi Rivers confirm a tendency towards more negative ϵ_{Nd} values with increasing grain size.
 554 Strong grain-size control on ϵ_{Nd} has been recently documented in Congo Fan sediments, where it was
 555 ascribed to the more negative ϵ_{Nd} carried by multiply recycled quartz grains originally derived from
 556 older terrains on average (figs. 6 and 8 in Garzanti et al. 2021b). In recycled Congo Fan sediments,
 557 however, quartz and monazite account for similar amounts of Nd, quartz being 10^5 times more
 558 abundant in weight but monazite containing 10^5 times more Nd. In first-cycle Lower Zambezi
 559 sediments, instead, heavy minerals (including monazite) are an order of magnitude more abundant
 560 than in Congo sediments, and are thus expected to dominate the REE budget (Totten et al. 2000).
 561 Among minerals frequently found in sediments, only monazite and allanite display very high LREE
 562 content, monazite being about three times richer in LREE. In our sample set, monazite resulted to be
 563 about five times more abundant than allanite, which implies an order-of-magnitude greater
 564 contribution to the LREE sedimentary budget by monazite than by allanite. The tendency of ϵ_{Nd} values
 565 to become more negative in sand, and more markedly in the 32-63 μm size class of Middle and Lower
 566 Zambezi sand samples, thus suggests that ultradense monazite, strongly concentrated in the fine tail

567 of the size distribution because of the settling-equivalence effect, carries an older (more negative) ϵ_{Nd}
 568 signal than other less dense and less durable minerals (e.g., allanite, titanite, apatite, epidote, and
 569 amphibole).

570 *Model Ages.* Depleted mantle model ages ($t_{Nd,DM}$) for the Zambezi mainstem and tributaries
 571 mainly range between 2.0 and 2.3 Ga (Fig. 6). Mud partly derived from Karoo basalt yielded notably
 572 younger values (1.6 Ga for Sinde and 1.45 Ga for Matetsi), as all size fractions of Shire sediment
 573 largely derived from mafic granulites of the Blantyre domain (1.25-1.45 Ga). Morrunguze sand
 574 largely derived from gabbroic rocks of the Tete domain yielded the youngest value (1.16 Ga), whereas
 575 the oldest values (2.5-2.8 Ga) characterize the three rivers sourced in the Archean Zimbabwe Craton
 576 (Gwai, Mazowe, and Luenha) (Fig. 6).

577 Sm-Nd model ages depend on REE fractionation, being lower in samples containing LREE-rich
 578 minerals such as monazite or allanite and higher in samples containing MREE-rich minerals such as
 579 xenotime, titanite or apatite (fig. 9 in Garzanti et al. 2021b). Because of the settling-equivalence
 580 effect, ultradense monazite grains occur only in the fine tail of the size distribution, which explains
 581 why the 32-63 μm size class of the cohesive Zambezi silt collected at Tete has a higher Sm/Nd ratio
 582 and thus yielded a notably higher Sm-Nd model age than the <32 μm fraction despite its slightly
 583 lower ϵ_{Nd} (Fig. 6). In the two Zambezi samples upstream of the delta, the 63-2000 μm fraction has
 584 lower LREE fractionation (higher Sm/Nd) than both 32-63 μm and < 32 μm fractions, and thus
 585 yielded older Sm-Nd model ages than the < 32 μm fraction despite ϵ_{Nd} values are similar, and almost
 586 the same Sm-Nd model ages than the 32-63 μm size class despite the latter yielded notably more
 587 negative ϵ_{Nd} (Fig. 6).

588

589 *Provenance Insights from Detrital-Zircon Geochronology*

590 Age spectra of detrital zircons enrich provenance information by providing insight into events of
 591 crustal growth in diverse source-rock domains (Fig. 10). In the general case, however, these can only
 592 be considered as “protosources” (Andersen et al. 2016, 2018). They represent the true sediment source

only in the specific case of first-cycle detritus supplied directly from igneous or metamorphic basement (Dickinson et al. 2009). This introduces a further major uncertainty in zircon-based provenance analysis, because most sedimentary basins are fed with a mixture of recycled and first-cycle sediments in a proportion that can be evaluated only roughly from independent compositional data.

Petrographic, mineralogical, and geochemical data collectively concur to reveal that Uppermost Zambezi sand is dominantly recycled from Kalahari dune fields (Garzanti et al. 2014b). The Kwando River in particular drains entirely within the Kalahari Basin, whereas some first-cycle detritus is supplied by Zambian tributaries sourced in the Lufilian arc or Choma-Kalomo Block. In sharp contrast, Lower Zambezi sand is mostly first-cycle and derived from igneous and metamorphic Precambrian basements rejuvenated during Neogene southward propagation of the East African Rift.

Zircon Ages. Geochronological analysis indicates the Irumide and Pan-African crustal domains as the main protosources of zircon grains in rivers draining the northern Kalahari Plateau (Fig. 7). Neoproterozoic ages ultimately derived from the Kasai Shield are common only for Kwando sand in the west. Paleoproterozoic grains ultimately derived from the Angola Block are more common in Kwando and Uppermost Zambezi sand than in eastern Zambian tributaries. Among these, Paleoproterozoic zircons are more common in Sinde sand sourced in the Choma-Kalomo Block, whereas Neoproterozoic zircons are much more abundant in Kasaya sand largely derived from the Lufilian Arc. The Irumide peak is invariably prominent. Zircon grains yielding Permian to Triassic Karoo ages constitute a minor population in Sinde sand but are lacking in Upper Zambezi sand downstream of the basaltic gorges, indicating that zircon occurs in tuffs interlayered within Karoo siliciclastic strata but not in the overlying Lower Jurassic basalt.

Despite extensive remobilization during the Pan-African orogeny (fig. 7 in Goscombe et al. 2020), the analysed center of zircon grains in sand of northern (Kafue, Luangwa, Morrunguze) and western (Sangara, Mufa) tributaries to the Middle and upper Lower Zambezi yielded mostly or even exclusively Irumide ages (Table 4). The dominant Irumide zircon-age peak displayed by Kafue sand

619 suggests that zircons sourced from the Neoproterozoic Lufilian Arc are retained in the Itezhi-Tezhi
 620 Reservoir and/or in the Kafue Flats and do not reach the lower gorge, where Irumide-aged zircons
 621 are derived largely from the Mpande Gneiss (~ 1.1 Ga; [Hanson et al. 1994](#); fig. 6 in [Goscombe et al.](#)
 622 [2020](#)).

623 Late Neoproterozoic ages are lacking in sand of the Morrunguze River draining entirely within
 624 the Southern Irumide Province but more abundant than Irumide ages in sand of the Shire and Zangue
 625 tributaries joining the Zambezi upstream of the delta ([Fig. 7](#)). Archean zircons are common ($24 \pm 2\%$)
 626 in the Gwai, Mazowe, and Luenha Rivers sourced in the Zimbabwe Craton. Gwai sand also carries
 627 $\sim 30\%$ of Paleoproterozoic zircons largely derived from the Dete-Kamativi Inlier cut across in the
 628 lower course.

629 The multimodal age-spectrum of Zambezi zircons eventually supplied to the delta and dragged
 630 by littoral currents to the northern Quelimane region indicates predominance of zircon grains derived
 631 directly or indirectly from the Irumide belt, with subordinate late Neoproterozoic zircons mainly
 632 supplied by geological domains most severely remobilized during the Pan-African orogeny ([Fig. 7](#)).
 633 Orosirian zircons are frequent, Neoarchean grains minor, and Permian-Triassic zircons rare ([Table](#)
 634 [4](#)).

635 A few Permian-Triassic zircons derived from Karoo volcanic or volcanoclastic layers are
 636 identified in Kasaya, Sinde, Gwai Kafue, and Luangwa sands, but were not recorded from any Lower
 637 Zambezi tributary. Yet, a few Permian-Triassic zircons occur in Lower Zambezi sand upstream of
 638 the delta, suggesting recycling of Karoo strata exposed in the Moatize-Minjova basin. Jurassic or
 639 Cretaceous ages are sporadically recorded. Among these, most significant are a couple of grains dated
 640 as ~ 120 Ma in the terminal tract of the Lower Zambezi, indicating provenance from igneous rocks
 641 emplaced during the incipient opening of the Mozambique Channel ([König and Jokat 2010](#); [Chanvry](#)
 642 [et al. 2018](#)).

643 **Zircon Fertility.** The joint consideration of petrographic, mineralogical, and geochemical
 644 datasets does not only offer a panorama of compositional signatures but also useful information to

645 evaluate the zircon fertility of sediment sources (e.g., diverse tributary catchments in the Zambezi
 646 drainage system), which is required for a correct use of zircon-age data in the calculation of
 647 provenance budgets. Ultradense zircon is invariably segregated in the fine tail of the size distribution
 648 of each sample deposited by a tractive current and can be strongly concentrated locally by selective-
 649 entrainment processes ([Garzanti et al. 2008, 2009](#)). These issues may hamper the accuracy of fertility
 650 determinations based on mineralogical or geochemical data ([Malusà et al. 2016](#)).

651 In our sample set, sands from the upper part of the Zambezi catchment have a notably lower
 652 concentration of zirconium (Zr 232 ppm in one trunk-river sample, but otherwise invariably below
 653 the UCC standard and mostly in the 30-80 ppm range) than in the Middle and Lower Zambezi
 654 catchment (between 330 and 600 ppm in Kafue and Mufa samples, and above the UCC also for the
 655 Middle Zambezi, Luenha, and Shire samples). Zircon concentration, calculated by combining
 656 petrographic and heavy-mineral point-counting data ([Appendix Tables A6 and A7](#)), is markedly
 657 lower in the Uppermost to Upper Zambezi catchment (median of bulk sand in volume 0.02%,
 658 maximum 0.2%), than in Middle to Lower Zambezi catchment (median 0.16%, maximum 0.6% for
 659 Shire sand).

660 A most useful parameter to detect hydraulically controlled concentration of denser minerals is
 661 the weighted average density of terrigenous grains in g/cm^3 (SRD index of [Garzanti and Andò 2007](#)),
 662 which for each sample should be equal to the weighted average density of source rocks in the ideal
 663 absence of environmental bias. The SRD index of most sands in rivers on the Kalahari Plateau ranges
 664 between 2.65 and 2.68 (just a little higher than quartz density), increasing to 2.79 and 2.90 for Masuie
 665 and Matetsi sands containing 50% and 70% of detritus from dense basaltic rocks. In the Middle to
 666 Lower Zambezi catchment, SRD mostly ranges between 2.7 and 2.8, which matches the expected
 667 density range for upper to middle crustal basement rocks ([Garzanti et al. 2006](#)). The finer-grained
 668 Kafue (SRD 2.79) and Luenha (SRD 2.78) sands are those richest in elements preferentially hosted
 669 in ultradense minerals ([Fig. 4](#)). Luenha sand has high LREE and Th, negative LOI, but only
 670 moderately high Zr, indicating concentration of ultradense monazite and magnetite but only

moderately high zircon content (0.16% of bulk sand in volume; [Appendix Table A7](#)). The higher SRD values observed for Shire (2.82) and Morrunguze sands (2.87) reflect contribution from high-grade and largely mafic basement rocks of the Blantyre and Tete domains (figs. 2 and 7 in [Goscombe et al. 2020](#)). Ultradense garnet, zircon, monazite, and opaque Fe-Ti-Cr oxides have been markedly concentrated by selective entrainment processes only in Lower Zambezi sample S5778 (SRD 3.34), a fluvial garnet placer not analysed for either geochemistry or zircon geochronology.

Petrographic, heavy-mineral, and geochemical data converge to indicate that the zircon concentration in our samples provides a broadly reliable indication of zircon fertility in the corresponding catchments. Zircon fertilities are estimated to range from 0.02% for Kalahari dune sands to 0.2% for mid-crustal basement rocks exposed in the Lower Zambezi catchment.

Provenance Budgets and Erosion Patterns

Provenance Budgets. In this section, independent calculations based on elemental-geochemistry, Nd-isotope, and geochronological data are used to better constrain the rough provenance budget based on detrital modes presented in [Garzanti et al. \(2021a\)](#). Integrated compositional data indicate that Upper Zambezi sand and silty sand delivered to Lake Kariba consist $\geq 80\%$ of recycled quartz-rich Kalahari dunes and $16\pm 4\%$ of largely basaltic volcanic detritus, the remaining $\leq 5\%$ being derived from Precambrian basements exposed in Zambia and Zimbabwe. The age spectrum of zircon grains supplied by the Upper Zambezi to Lake Kariba is intermediate between those of Uppermost Zambezi and Kwando sands. These two river branches are thus revealed as the most prominent zircon sources, in a relative proportion that cannot be accurately determined owing to the low and similar zircon concentration in their sands indicated by mineralogical and geochemical data ([Table 2](#)).

Because sand generated in the Upper and Middle Zambezi catchments is trapped in Lakes Kariba and Cahora Bassa, all sand ultimately delivered to the delta (zircon grains included) is generated within the Lower Zambezi catchment. Petrographic and heavy-mineral data indicate contribution in similar proportion (ca. 30-40% each) from the Southern Irumide Province drained upstream of the

697 Luenha confluence and from the Mazowe-Luenha river system sourced in the Zimbabwe Craton. The
 698 Umkondo Belt and the Karoo, Cretaceous, and Cenozoic extensional basins drained by the Minjova,
 699 Sangadze, and Zangue tributaries contribute much of the rest (~20%), whereas supply from the Tete
 700 and Blantyre domains drained respectively by the Morrunguze and Shire tributaries is subordinate
 701 ($\leq 10\%$ each; [Garzanti et al. 2021a](#)).

702 New complementary information obtained from elemental geochemistry suggests that as much
 703 as 70% of Lower Zambezi sand may be supplied by the Mazowe-Luenha river system, with
 704 subordinate contribution from the mainstem upstream of the Zambezi-Luenha confluence (20-25%),
 705 and minor supply from the Morrunguze and Shire Rivers ($< 5\%$ each) and other lowermost-course
 706 tributaries (~5%). Calculations based on ϵ_{Nd} values of sand (63-2000 μm fraction) confirm that most
 707 Lower Zambezi sand is generated in the Mazowe-Luenha catchment (55-65%), with subordinate
 708 contribution from the mainstem upstream of the Luenha confluence and other sources. The ϵ_{Nd} values
 709 of cohesive mud ($< 32 \mu m$ fraction) in the Lower Zambezi upstream of the delta are similar or more
 710 negative than for sand ([Table 3](#)), indicating that mud contributions from the Mazowe-Luenha river
 711 system are not lower, and possibly higher, than for sand.

712 Forward mixing calculations based on zircon-age data suggest that at least half of zircon grains
 713 are derived from the Irumide domain, a quarter at most is generated in the Mazowe-Luenha
 714 catchment, and a fifth at most in the final part of the Zambezi drainage basin, with minor contribution
 715 from the Shire River. Because mineralogical and geochemical data indicate a relatively high zircon
 716 fertility for the Shire catchment, all compositional information converges to indicate that the Shire
 717 River supplies only a very small part ($< 5\%$) of sediment to the Zambezi Delta. This holds true also
 718 for mud, because the smectite/kaolinite ratio increases sharply downstream of the Lower Zambezi,
 719 whereas Shire mud contains abundant kaolinite and minor smectite ([Table 1](#)). Minor sediment supply
 720 from the Shire River is explained by sequestration in Lake Malawi of all sediment generated in the
 721 upper catchment and by further sediment trapping in wetlands and artificial reservoirs downstream
 722 ([Mzuza et al. 2019](#)). This inference contrasts with [Just et al. \(2014 p.191\)](#), who reckoned that the

723 Shire River contributes ~28% of total Zambezi sediment load at present (~21% before construction
724 of the Cahora Bassa Dam).

725 *Weighing up Information.* Provenance budgets based on independent datasets and on diverse size
726 fractions are not entirely consistent. Age spectra of detrital zircons point at predominant zircon supply
727 from the Irumide domain exposed in the upper part of the Lower Zambezi catchment, with minor
728 zircon contribution from the Zimbabwe Craton drained by the Mazowe and Luenha Rivers. Instead,
729 elemental-geochemistry and Nd-isotope data suggest that most Lower Zambezi sediment is generated
730 in the Mazowe-Luenha catchment. Although the robustness of diverse sets of calculations is not easily
731 evaluated, it notably increases if end-member signatures are well distinct, precisely determined, and
732 have little variability dependent on grain size, weathering, or hydraulic sorting. Conversely, estimates
733 obtained on a narrow grain-size window or, worse, on a rare mineral within a narrow grain-size
734 window, are least likely to be representative and accurately extrapolated to the entire sediment flux
735 ([Vezzoli et al. 2016](#)).

736 In the case of Lower Zambezi tributaries draining medium/high grade crystalline basements,
737 sand-petrography, heavy-mineral, and elemental-geochemistry signatures show significant overlap
738 and hydrodynamically-controlled variability. Least robust are calculations based on zircon-age
739 spectra, because of the uncertainties involved in zircon-fertility determinations. Nd-isotope
740 geochemistry suffers from a limited number of analysed samples, but the end members are well
741 distinct and precisely defined, all grain sizes have been considered, and grain-size-dependent
742 variability is limited ([Fig. 9](#)). The change towards much more negative ϵ_{Nd} documented in all size
743 fractions of Lower Zambezi sediments downstream of the Luenha confluence cannot be ascribed to
744 Shire sediments — which yielded even less negative ϵ_{Nd} values for all size fractions ([Fig. 6](#)) — but
745 clearly indicates major sediment supply from the Mazowe-Luenha river system. Weighing up all
746 obtained information, we conclude that up to two-thirds of the sediment presently reaching the
747 Zambezi Delta is generated in the Mazowe-Luenha catchment, between a quarter and a third is

748 produced between Lake Cahora Bassa and the Zambezi-Luenha confluence, and the rest downstream,
 749 with very limited supply ($\leq 5\%$) from the Shire River.

750 ***Erosion Patterns.*** Because of a general lack of gauged sediment loads, Zambezi sediment fluxes
 751 are evaluated with large uncertainties of a full order of magnitude. Erosion patterns across the
 752 catchment can thus be only grossly determined. Based on the available sediment-concentration data
 753 and sediment-transport models, two end-member domains can be distinguished by their contrasting
 754 geomorphological conditions and sediment-generation modality: the low-relief Kalahari Plateau
 755 largely covered by eolian sand in headwater regions *versus* rugged igneous and metamorphic terranes
 756 extensively exposed between Victoria Falls and Mozambican lowlands.

757 On the plateau, rivers with low channel steepness sluggishly flow for large tracts through
 758 wetlands, where sediment is sequestered rather than produced, as in the Barotse floodplain and Chobe
 759 marshes on the mainstem or in the Machili and Kafue Flats traversed by the Kasaya, Ngwezi, and
 760 Kafue tributaries. Because data on Kwando sediment load are to the best of our knowledge
 761 unavailable, information from the Okavango River similarly draining entirely within the Kalahari
 762 Basin in Angola ([Shaw and Thomas 1992](#); [McCarthy et al. 2012](#)) allows us to broadly constrain the
 763 annual sediment yield and erosion rate in the Kalahari Basin as 2 ± 2 tons/Km² and 0.001 ± 0.001 mm.
 764 This is notably lower than estimates based on cosmogenic nuclides for the Uppermost Zambezi
 765 catchment including Precambrian terranes in the north (16 ± 2 tons/Km² and 0.006 ± 0.001 mm;
 766 [Wittmann et al. 2020](#)). Sediment yield increases by an order of magnitude where channel steepness
 767 reaches very high values, as in basaltic gorges downstream of Victoria Falls ($40\text{--}90$ tons/Km²; fig. 3
 768 and p.356 in [Garzanti et al. 2021a](#)).

769 A similar sediment-generation pattern characterizes other rivers flowing on the Kalahari Plateau
 770 in the headwaters and plunging into bedrock gorges downstream. For the Gwai River, a provenance
 771 budget based on petrographic, heavy-mineral, and geochemical data on both fluvial-bar and levee
 772 silty sands indicates that sediment yield and erosion rate are between 20 and 50 times higher in the
 773 lower course cutting steeply across the Dete-Kamativi Inlier of the Magondi Belt than in the upper

774 course, sourced in the Zimbabwe Craton and draining the Kalahari Basin. The same may hold true
 775 for the Kafue River, where much of the sediment is however trapped in the Kafue Flats and behind
 776 the Itezhi-Tezhi and Kafue Gorge Dams.

777 Annual yields of 150 ± 50 tons/Km², corresponding to erosion rates of 0.06 ± 0.02 mm, were
 778 estimated for Middle and Lower Zambezi tributaries flowing steeply across basement rocks exposed
 779 in the Archean Zimbabwe Craton or in the Proterozoic Irumide, Umkondo, and Zambezi Belts in
 780 southern Zambia, northeastern Zimbabwe, and western Mozambique (Bolton 1984; Ronco et al.
 781 2010). Considering that the Lower Zambezi upstream of the Luenha confluence and the Mazowe-
 782 Luenha river system have similar catchment areas, our provenance budget implies sediment yields
 783 and erosion rates between 1.5 and 2.5 times higher in the latter. Extensive sediment trapping in Lake
 784 Malawi upstream and across wetlands or behind dams downstream (Mzuza et al. 2019) prevents us
 785 to make considerations concerning erosion rates in the Shire catchment.

786

787

Weathering *versus* Recycling

788 *Insights from Clay Minerals.* Clay mineralogy is quite sensitive to weathering conditions. It has
 789 long been observed that kaolinite is abundant in hot humid regions where feldspar hydrolysis is
 790 intense, whereas smectite is common in warm regions with a dry season characterized by intense
 791 evaporation, and illite and chlorite dominate where chemical decomposition is minor (Chamley 1989;
 792 Velde 1995). In modern sediments, the ratio between kaolinite and illite+chlorite [Kao/(Ill+Chl)] may
 793 thus be used as a proxy for weathering intensity (Liu et al. 2007; He et al. 2020). Within our sample
 794 set, kaolinite is significant in all catchments and represents ~40% of the clay-mineral assemblage in
 795 Uppermost Zambezi, Lower Zambezi (Tete sample), and Shire mud (Fig. 3). The Kao/(Ill+Chl) ratio
 796 is > 1 in Uppermost Zambezi, Kwando, Ngwezi, and upper Gwai muds generated on the Kalahari
 797 Plateau, but < 1 in Middle and Lower Zambezi tributaries downstream (Table 1).

798 *Insights from Mud and Sand Geochemistry.* Geochemical indices have long been used as
 799 proxies for weathering intensity (e.g., Nesbitt and Young 1982; Price and Velbel 2003), although they

may be even predominantly controlled by grain size (von Eynatten et al. 2012, 2016), provenance (Garzanti and Resentini 2016; Dinis et al. 2017), hydraulic sorting, or quartz addition by recycling (Fig. 11). This is especially true for sand, and weathering conditions are thus better reflected in the geochemistry of mud (Dinis et al. 2020b).

A most reliable indicator of weathering intensity is $\alpha^{\text{Al}}\text{Na}$, which chiefly measures the progressive leaching of Na^+ from the plagioclase lattice. The $\alpha^{\text{Al}}\text{Na}$ value decreases quite regularly from the Uppermost Zambezi and Kwando Rivers (21-22 for mud, ≥ 4 for sand) to Victoria Falls (4.6 for mud, 2.1 ± 0.1 for sand), and to the Middle and Lower Zambezi (4.6 ± 0.4 for mud, 1.2 ± 0.1 for sand). Other α^{Al} values, and consequently the CIA* and its several derivative indices, are more significantly affected by the mineralogy of sediment sources. Most evident is the anomaly of Kwando mud, which is notably enriched in Ca, Sr, Mg, and Ba derived from erosion of calcrete soils (Fig. 11) and consequently yielded very low corresponding α^{Al} indices (≤ 0.4). Masuie, Matetsi, and Morrunguze sediments largely derived from basaltic or gabbroic rocks have high Mg and Ca and consequently low $\alpha^{\text{Al}}\text{Mg}$ and $\alpha^{\text{Al}}\text{Ca}$ (0.4-0.6). Conversely, sediments derived from gneissic basements are enriched in K and Rb largely hosted in K-feldspar and mica, which explains why $\alpha^{\text{Al}}\text{K}$ and $\alpha^{\text{Al}}\text{Rb}$ are < 1 in several tributaries (e.g., Kasaya, Ngwezi, Gwai, Kafue, Luangwa, Mazowe, Luenha, and Sangadze). Sangadze sediments have the lowest plagioclase/K-feldspar ratio of all analysed sands from the Lower Zambezi catchment, and consequently yielded the highest $\alpha^{\text{Al}}\text{Na}$ in both mud and sand, and the lowest $\alpha^{\text{Al}}\text{K}$ and $\alpha^{\text{Al}}\text{Rb}$ in sand.

Insights from Detrital Minerals. Additional indications on weathering intensity can be inferred from the different durability of detrital minerals, although this path is fraught with pitfalls. An example is the unfortunate use of the “Mineralogical Index of Alteration” [$\text{MIA} = \text{Q}/(\text{Q} + \text{F}) \times 100$; Rieu et al. 2007], a misleading parameter not only long demonstrated to markedly increase with grain size (Odom et al. 1976) but also reaching maximum values equally in hyper-humid equatorial and hyper-arid desert conditions (Garzanti et al. 2019; Pastore et al. 2021).

825 The different chemical durability of heavy minerals is more reliably indicative (Bateman and
 826 Catt 2007). Particularly useful is the ratio between garnet (G) and other nesosilicates found in
 827 amphibole-facies metapelites (SKAS = staurolite + kyanite + andalusite + sillimanite), which in sand
 828 of the Lower Zambezi catchment [$G/(G+SKAS) = 72 \pm 21\%$] is the same as in modern first-cycle sand
 829 derived from metamorphic basements [$G/(G+SKAS) = 70 \pm 20\%$; Garzanti et al. 2010a]. In contrast,
 830 the markedly anomalous low ratios [$G/(G+SKAS) < 5\%$] that characterize sand in the Uppermost
 831 Zambezi catchment testify to an almost complete breakdown of garnet, a mineral that proves to be
 832 extremely vulnerable in equatorial soils (figs. 9C and 9D in Garzanti et al. 2013a) but very durable
 833 in dry tropical climate (Garzanti et al. 2015). In recycled sand of the Kalahari Plateau, even zircon
 834 results to be selectively weathered out relative to quartz, as indicated by a zircon concentration lower
 835 by an order of magnitude relative to first-cycle sand shed by Precambrian basement rocks in the
 836 Middle to Lower Zambezi catchment. Zircon depletion is chiefly ascribed to breakdown of
 837 preferentially weathered, strongly metamict old grains (e.g., Balan et al. 2001; Resentini et al. 2020).

838 *Corrosion features.* Direct evidence of chemical attack is provided by surficial dissolution
 839 textures on labile ferromagnesian minerals (Velbel 2007). This approach, however, has drawbacks:
 840 i) surficial features tell us the state of what is preserved but nothing about how much was destroyed;
 841 ii) fresh and strongly weathered grains of the same detrital mineral commonly occur jointly (Van
 842 Loon and Mange 2007); iii) slight degrees of corrosion may not be evaluated consistently by different
 843 operators. Only semiquantitative hints on the intensity of weathering can thus be obtained.

844 With this aim, the percentage of surficially etched grains and the degree of corrosion was
 845 recorded for over 4000 identified transparent heavy minerals following the classification of Andò et
 846 al. (2012). In Uppermost Zambezi mainstem and tributaries, pyroxene, amphibole, epidote, staurolite,
 847 kyanite, and andalusite are all mainly unweathered, a minority of grains are corroded, and only a few
 848 pyroxene grains are deeply etched. In the Upper Zambezi mainstem and tributaries, most grains are
 849 unweathered, but the percentage of corroded grains increases and both pyroxene and amphibole may
 850 be deeply etched. In the Middle Zambezi mainstem and tributaries, the percentage of corroded heavy

851 minerals increases further, a larger percentage of pyroxene and amphibole grains are deeply etched,
 852 and also epidote, garnet, or kyanite may show deep etching. Similar features characterize Lower
 853 Zambezi mainstem and tributary sands, where epidote and garnet are even more extensively corroded.

854 ***Recycled Weathering Signatures.*** In the Uppermost Zambezi and Kwando Rivers, sand consists
 855 of quartz and durable heavy minerals, with very low $G/(G+SKAS)$ ratio, and $CIA^* > 75$; mud contains
 856 abundant kaolinite, CIA^* is > 80 , and $\alpha^{Al}Na$ is > 20 . Such compositional features, typical of sediment
 857 produced in hot-humid equatorial climate, are at odds with the semiarid conditions of the Kalahari
 858 Plateau today. They testify to an intensity of chemical weathering that cannot occur in the present
 859 climatic regime but must have been inherited through multiple recycling from much wetter conditions
 860 of the past, most plausibly characterizing the subequatorial belt to the north (Garzanti et al. 2022).
 861 Diagenesis between sedimentary cycles contributed too, but cannot account for all features (e.g.,
 862 virtually complete selective breakdown of garnet). Weathered detritus from lower latitudes ($\sim 10^\circ S$),
 863 for instance, was supplied to the Kalahari Basin by the once connected Chambeshi-Kafue river
 864 system, reaching the Uppermost Zambezi *via* the Machili Flats as supported by fish lineages (Moore
 865 and Larkin 2001; Katongo et al. 2005).

866 Clay-mineral assemblages in river muds across southern Africa are not kaolinite-dominated,
 867 reflecting the limited efficiency of soil-forming processes and incomplete feldspar leaching under the
 868 present climatic conditions (Garzanti et al. 2014a). Kaolinite must thus be largely recycled from
 869 widespread relic lateritic paleosols and duricrusts (Partridge and Maud 1987; Dill 2007; Moore et al.
 870 2009). Even in southern Malawi — where annual rainfall increases eastwards from ~ 0.8 m to 1.6 m
 871 at the foot of Mount Mulanje and up to 2.8 m at high elevation (peak 3002 m a.s.l.) — kaolinite is
 872 mostly recycled by fluvial incision of peneplains of Cretaceous to Cenozoic age triggered by base-
 873 level lowering of the Shire River (Dill et al. 2005). This is corroborated by the great abundance of
 874 fresh feldspar in Shire sand (fig. 5G in Garzanti et al. 2021a), where inefficient plagioclase hydrolysis
 875 is testified by undepleted Na and Ca ($\alpha^{Al}Na = \alpha^{Al}Ca = 1.0$).

876 All mineralogical and geochemical parameters, including $Kao/(Ill+Chl)$, CIA^* and $\alpha^{Al}Na$, would
 877 consistently indicate that weathering intensity recorded in modern river sediments decreases
 878 downstream the Zambezi River. Even when depurated from the physical effect of recycling (i.e.,
 879 quartz addition), mud generated in the Uppermost Zambezi catchment appears to be more affected
 880 by weathering than Middle and Lower Zambezi mud (Fig. 11). Such evidence, however, by no means
 881 implies that weathering on the dry Kalahari Plateau is at present more intense than in the wetter
 882 Middle to Lower Zambezi catchment. Rather, this trend reflects mixing of distilled polycyclic detritus
 883 originally generated during some wetter stages of the past to the north of the Kalahari dryland with
 884 first-cycle detritus shed from Karoo basalts along the Upper Zambezi, followed by abrupt
 885 replacement — downstream of Lake Kariba first and of Lake Cahora Bassa next — by largely first-
 886 cycle detritus derived from Precambrian basements. Only in the Middle and Lower Zambezi, where
 887 detrital minerals are directly derived from basement rocks, their surficial dissolution textures chiefly
 888 reflect present conditions of weathering. Together with trends displayed by cohesive mud (Fig. 11B),
 889 these are the only features that document a slight increase in weathering intensity from the Middle to
 890 the Lower Zambezi catchment.

891

892 **Conclusions**

893

894 Any compositional parameter is invariably controlled by multiple physical and chemical
 895 processes that must be carefully evaluated before provenance and environmental information could
 896 be correctly detangled and understood. Diverse datasets obtained by a range of independent methods
 897 were thus integrated to constrain the many unknowns, reduce the number of potential alternative
 898 solutions, and increase the plausibility of our inferences. Following this rationale, we applied a
 899 spectrum of mineralogical, geochemical, and geochronological techniques to shed light on
 900 sedimentary processes active in the complex Zambezi big-river system.

901

902 In this study, such an approach allowed us to: 1) characterize the composition of mud and sand
 generated in, and transported across, the Zambezi drainage basin; 2) monitor the evolution of

903 compositional signals across a routing system rigidly segmented by both natural (tectonic
 904 depressions, lakes, wetlands) and anthropic factors (large reservoirs trapping all sediment generated
 905 upstream); 3) make inferences on sediment yields and erosion rates even in the lack of gauged
 906 sediment fluxes; 4) assess the intensity of weathering and the origin of weathering signatures (i.e.,
 907 present vs. recycled) in diverse parts of the vast catchment.

908 The age spectra of detrital zircons reflect the major episodes of crustal growth in Precambrian
 909 southern Africa. Irumide ages are dominant in the Lower Zambezi and in most of its tributaries,
 910 excepting the Shire and the Zangue Rivers where Pan-African ages prevail. Neoarchean ages
 911 characterize the Gwai, Mazowe and Luenha Rivers sourced in the Zimbabwe Craton. Eburnean ages
 912 are widely distributed but never prevail. Permian-Triassic (Karoo) ages are minor and Cretaceous
 913 ages rare.

914 Smectite is the most widespread clay mineral, dominant in mud from Karoo basalts as in the
 915 warm and poorly drained Mozambican lowlands characterized by equatorial/winter-dry climate. Illite
 916 is prevalent locally (e.g., Kafue mud) and kaolinite is ubiquitous, reaching maximum abundance in
 917 both uppermost and lower parts of the Zambezi catchment. Elemental geochemistry reflects
 918 overwhelming quartz addition by recycling of Kalahari dune sand in the Uppermost Zambezi, local
 919 supply from Lower Jurassic Karoo basalt in the Upper Zambezi, and chiefly first-cycle provenance
 920 from Precambrian basements in the Lower Zambezi.

921 The ϵ_{Nd} values range from mildly negative for sediment derived from Stenian gabbro, Tonian
 922 mafic granulite and Jurassic basalt to strongly negative for sand derived from Neoarchean cratonic
 923 gneiss. The preferential concentration of ultradense monazite in the fine tail of the size distribution
 924 owing to the settling-equivalence effect controls the intrasample ϵ_{Nd} variability among cohesive mud
 925 ($< 32 \mu m$), very coarse silt ($32-63 \mu m$), and sand fractions ($63-2000 \mu m$) as well as deviations from
 926 the theoretical relationships between ϵ_{Nd} and $T_{Nd,DM}$ model ages, suggesting that durable monazite
 927 carries a more negative ϵ_{Nd} signal than other REE-bearing minerals (e.g., allanite, titanite, apatite,
 928 epidote, and amphibole).

929 Elemental and isotope geochemistry reveal that 55-65% of mud and sand reaching the Zambezi
 930 Delta today, after the construction of the Kariba and Cahora Bassa Dams, is generated in the Mazowe-
 931 Luenha catchment. Contribution from Irumide terranes exposed upstream of the Luenha confluence
 932 is subordinate and supply from the Shire River – the outlet of Lake Malawi – is minor. Although an
 933 accurate assessment of sediment yields and erosion rates is hampered by the lack of gauged sediment
 934 fluxes, annual estimates are lower by an order of magnitude on the Kalahari Plateau (10-20 tons/Km²
 935 and ~0.005 mm) than in rugged terranes exposing Precambrian basements downstream (100-200
 936 tons/Km² and ~0.05 mm).

937 All mineralogical [garnet/(staurolite+kyanite+andalusite+sillimanite), kaolinite/(illite+chlorite)]
 938 and geochemical parameters (CIA*, $\alpha^{\text{Al}}\text{Na}$) consistently point to an intensity of chemical weathering
 939 on the Kalahari Plateau that cannot be related to modern dry-climate conditions. Chemical breakdown
 940 of virtually all minerals relative to quartz – including feldspars, garnet that is very labile in lateritic
 941 soils, and even zircon if strongly metamict – cannot occur in the Kalahari dryland, where kaolinite is
 942 recycled. Kaolinite is mostly produced by fluvial incision of relic Cretaceous-Cenozoic paleosols
 943 even in the Shire catchment closer to the wetter Mozambican coast, where inefficient plagioclase
 944 hydrolysis is testified by the dominance of fresh feldspars and undepleted Ca and Na. Indications of
 945 only slightly increasing weathering conditions in the Middle to Lower Zambezi catchment at present
 946 times are provided by mud geochemistry and surficial corrosion of pyroxene, amphibole, epidote,
 947 kyanite, and garnet.

948

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956

957 SUPPLEMENTARY MATERIAL

958 Supplementary data associated with this article, to be found in the online version at
959 http://dx.doi._____, include information on sampling sites (Table A1) together with clay
960 mineralogy (Table A2), elemental geochemistry (Tables A3 and A4), Nd-isotope geochemistry
961 (Table A5), bulk petrography (Table A6), and heavy-mineral datasets (Table A7). Appendix A
962 contains the caption of appendix tables and further information on the rationale of forward mixing
963 calculations. The complete detrital-zircon geochronology dataset is contained in Appendix B. The
964 Google-EarthTM map of sampling sites [Zambezi2.kmz](#) is also provided.

965

966 DATA AVAILABILITY

967 The mineralogical, geochemical, and geochronological datasets from this study are also available
968 from the senior author upon request.

969 FIGURES

970 **Figure 1.** The Zambezi drainage basin (base map from Google Earth™). White circles indicate
 971 sampling locations (more information in file [Zambezi2.kmz](#)). VF = Victoria falls.

972 **Figure 2.** Geology and climate of southern Africa. **A)** Geological map ([Thiéblemont et al. 2016](#)). **B)**
 973 Precipitation gradients: east/west from warm Indian Ocean to cool Atlantic Ocean; south/north from
 974 Kalahari dryland to humid Congo. **C)** Distribution of climatic zones (Köppen–Geiger classification;
 975 [Kottek et al. 2006](#)): A = equatorial; B = arid; C = warm temperate. Precipitation: W = desert; S =
 976 steppe; f = fully humid; s = summer dry; w = winter dry. Temperature: h = hot arid; k = cold arid; a
 977 = hot summer; and b = warm summer.

978 **Figure 3.** Clay mineralogy. Multiple controls explain erratic trends (dotted arrow) downstream the
 979 Zambezi River (stars). Recycled kaolinite occurs in both Uppermost Zambezi and Lower Zambezi
 980 catchments (e.g., Shire mud). Smectite is derived from Karoo basalt around Victoria Falls (VF) but
 981 also produced on the Kalahari Plateau and Mozambican lowlands (e.g., Sangadze mud). Illite is
 982 derived from metasedimentary and siliciclastic rocks of the Irumide and Pan-African belts (e.g.,
 983 Kafue and Tinde muds).

984 **Figure 4.** Sand and mud geochemistry (in UCC-normalized diagrams chemical elements are arranged
 985 following the periodic table group by group). **A, B)** In Zambezi headwaters, extensive quartz addition
 986 by recycling explains relative depletion of most elements other than Si in sand. Supply from Karoo
 987 basalt leads to marked increase in ferromagnesian metals and lack of Eu anomaly. High Ca, Sr, Mg,
 988 and Ba in Kwando mud reflect reworking of calcrete soils. **C, D)** Kafue samples are slightly enriched
 989 in elements hosted in ultradense minerals. Umguza and Upper Gwai sediments include minor detritus
 990 from Karoo basalt. Luangwa sand is partly recycled from Karoo siliciclastic strata. **E, F)** Most Lower
 991 Zambezi tributaries carry sediment undepleted relative to the UCC. In Morrunguze sand, high
 992 ferromagnesian metals and lack of Eu anomaly reflect supply from the Tete gabbro-anorthosite. High
 993 LREE and Th in Luenha sand suggest presence of monazite. **G, H)** Recycled quartz decreases

994 downstream the Zambezi mainstem. Lower Zambezi sand is only moderately depleted relative to the
 995 UCC, and mud is undepleted.

996 **Figure 5.** Rare Earth Elements. **A, B, C)** Chondrite-normalized REE patterns for sand. HREE trends
 997 are ill defined in pure quartzose sand because of very low concentration of elements with odd atomic
 998 numbers (Tb, Ho, Tm, Lu). **D, E, F)** Chondrite-normalized REE patterns for mud. **G, H, I)** $\text{La}_\text{N}/\text{Yb}_\text{N}$
 999 *versus* europium anomaly. **J, K, L)** LREE versus HREE fractionation. Mafic detritus, conspicuous in
 1000 Matetsi, Masuie and Morrunguze sediments and present in Sinde, Umguza, and Uppert Zambezi
 1001 sediments, has higher REE concentration, lower LREE fractionation, no Eu anomaly, and higher
 1002 HREE fractionation. Absence of Eu anomaly in most Lower Zambezi sands reflects abundance of
 1003 Ca-bearing feldspar. Steepest REE patterns with strongly negative Eu anomaly in Luenha sand
 1004 indicates presence of monazite, whereas strongly positive Eu anomaly in Sangadze sand reflects
 1005 abundant feldspar with lesser quantities of heavy minerals.

1006 **Figure 6.** Relationship between $\epsilon_{\text{Nd}(0)}$ and depleted mantle model ages ($T_{\text{Nd,DM}}$) for the Zambezi
 1007 mainstem and tributaries. The ϵ_{Nd} and $T_{\text{Nd,DM}}$ values are least negative and youngest for detritus from
 1008 Karoo basalt, Tete gabbro, and Blantyre mafic granulite (emplacement ages after [Svensen et al. 2012](#),
 1009 [Westerhof et al. 2008](#), and [Goscombe et al. 2020](#), respectively), and most negative and oldest for
 1010 detritus from Neoproterozoic cratonic gneiss. Most samples have higher Sm/Nd ratio than the UCC and
 1011 thus plot below the red line (based on $\text{Sm}/\text{Nd}_{\text{UCC}} = 0.1735$). The 32-63 μm size class of sand samples,
 1012 representing the fine tail of the size distribution where ultradense monazite is concentrated, has high
 1013 LREE and steeper LREE pattern (lower Sm/Nd) than the 63-2000 μm fraction. Instead, the 32-63 μm
 1014 size class of the Lower Zambezi silt collected at Tete (yellow outline) has low LREE and high Sm/Nd
 1015 because it represents the coarse tail of the size distribution depleted in ultradense minerals.

1016 **Figure 7.** U-Pb age spectra of detrital zircons. Archean ages are common in Gwai, Mazowe and
 1017 Luenha sands sourced in the Zimbabwe Craton. Orosirian ages in Kwando and Uppermost Zambezi
 1018 sands recycling Kalahari dunes and in Gwai sand largely derived from the Paleoproterozoic Magondi

1019 Belt. Irumide ages are widespread, overwhelming in Sangara and Morrunguze sands and dominant in
 1020 Lower Zambezi sand. Pan-African zircons are also widespread, but only locally prevalent (Shire and
 1021 Zangue sands). Geological domains after [Hanson \(2003\)](#) and [Thiéblemont et al. \(2016\)](#). CK = Choma-
 1022 Kalomo block; IB = Irumide Belt; KB = Kibaran Belt; LRZ = Luangwa Rift Zone; MB = Magondi
 1023 Belt; MRZ = Malawi Rift Zone; SIP = South Irumide Province; UB = Umkondo Belt; Ub-Usg =
 1024 Ubendian-Usagaran Belts.

1025 **Figure 8.** The biplots highlight the relationships among chemical elements in Zambezi sand and
 1026 cohesive mud. Provenance control is most evident for sand. Ferromagnesian metals are enriched in
 1027 basaltic or gabbroic detritus, Al, Na, Ca, K, Rb, Ba, and Eu hosted in feldspars are enriched in first-
 1028 cycle detritus from mid-crustal basements, and Si, Zr, and Hf in sediment recycled from Kalahari
 1029 dunes dominated by quartz and durable heavy minerals.

1030 **Figure 9.** Multiple controls on Nd isotope values. Most prominent are the effects of lithology (mafic
 1031 detritus being least negative) and average age of source rocks (as highlighted by generally good
 1032 correlation with U-Pb age of detrital zircon). Grain-size-controlled intrasample variability is limited.

1033 **Figure 10.** Multidimensional scaling map based on U-Pb zircon-age spectra (green field defined by
 1034 two Lower Zambezi samples upstream of the delta and Praia da Madal beach). Irumide ages are
 1035 dominant in Sangara and Morrunguze sands. Pan-African ages prevail in Shire and Zangue sands.
 1036 Neoarchean ages prevail in Gwai sand and are common in Luenha and Mazowe sands. Eburnean ages
 1037 are common in Upper Zambezi, Kwando, and Gwai sands but never prevalent. A few Karoo ages
 1038 occur in Kasaya and Sinde sands. Closest and second closest neighbours are linked by solid and
 1039 dashed lines, respectively.

1040 **Figure 11.** Discriminating the effects of weathering, recycling, and grain size from geochemical data.
 1041 Theoretical trends are calculated starting from the UCC standard: quartz-addition trend by
 1042 progressively adding SiO₂; weathering trend by progressively subtracting mobile metals relative to Si
 1043 and Al. Grain-size trend based on data from Alpine and Himalayan sediments ([Garzanti et al. 2010b](#),

2011, 2012). In all four panels, sand follows the quartz-addition trend reflecting recycling of Kalahari sands (Uppermost and Upper Zambezi catchment) or Karoo and older sandstones and metasandstones (Middle and Lower Zambezi catchment) to various degrees. Mud samples broadly follow the weathering trend. **A)** Samples plotting far below the regression line ($\text{Al}_2\text{O}_3 = -0.45 \text{ SiO}_2 + 45$) include Fe-rich Masuie and Matetsi sands from Karoo basalts, and Kwando mud enriched in Ca, Sr, Mg, and Ba from calcrete soils. **B)** Uppermost and Upper Zambezi muds plot below the weathering trend (low WIP), suggesting weathering signature inherited by recycling. Middle and Lower Zambezi muds follow the theoretical trend, hinting at slightly increasing weathering intensity toward the coast. Calcrete erosion explains anomalously low CIA* in Kwando mud. **C, D)** Cohesive muds collected upstream of Lake Kariba reflect quartz addition from Kalahari dunes (Uppermost Zambezi) or Neoproterozoic sandstones (Tinde).

Table 1. Silt and clay mineralogy in the Zambezi catchment determined by X-ray powder-diffraction. Qz = quartz; KF = K-feldspar; Pl = plagioclase; Carb = carbonate; Amp = amphibole; Hem = hematite; Phyll = phyllosilicate; Sme = smectite; Ill = mica/illite; Chl = chlorite (including vermiculite); Kao = kaolinite.

Table 2. Sand and mud geochemistry in the Zambezi catchment. LOI = loss on ignition. The α values are defined as $(\text{Al}/\text{E})_{\text{sample}}/(\text{Al}/\text{E})_{\text{UCC}}$. CIA* values corrected only for CaO in apatite.

Table 3. Neodymium isotope values and Sm-Nd model ages for cohesive mud ($> 32 \mu\text{m}$), very coarse silt ($32\text{-}63 \mu\text{m}$), and sand ($63\text{-}2000 \mu\text{m}$) fractions of Zambezi sediments (FS = fine sand; VFS = very fine sand). * = data from mud samples collected in the upper part of the Zambezi catchment after Garzanti et al. (2014a). All other data are from sand samples excepting the Lower Zambezi silt collected at Tete.

Table 4. U-Pb age peaks of detrital zircons and relative frequencies in modern sands of the Zambezi catchment (calculated with Density Plotter; Vermeesch, 2012). To treat all samples equally and avoid bias in intersample comparison the laser spot was always placed blindly in the center of zircon grains.

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To the Editor of
The Journal of Geology

Dear Sir,

please find enclosed the very carefully revised version of our manuscript, entitled “*The Segmented Zambezi Sedimentary System from Source to Sink - 2. Geochemistry, Clay Minerals, and Detrital Geochronology*” and submitted for publication in **The Journal of Geology**. This article integrates with new major and trace element geochemistry, Nd isotope, clay mineral, and U-Pb detrital-zircon age data the recently published study focused on sand petrology and heavy minerals, thus completing our multidisciplinary research project dedicated to the sedimentary system of the Zambezi River.

The manuscript has been thoroughly revised taking into full account the constructive critical comments provided by all three Reviewers, who greatly helped us to check every detail and to amend the flaws that the submitted version contained. The comments provided by Reviewer Basu were given particular attention. We did not eliminate figures but carefully checked, corrected, and improved all of them. As required, we added a new Table 4 providing key numerical information on zircon age-peaks. The account on how we have responded to the concerns expressed by each Reviewer is detailed point-by-point in the separate file “*Zambezi 2 Revision Notes*”.

We thank you heartily for your precious help, attention, and kind interest, hoping that our revised manuscript is now in current order and can thus meet the high requirements of **The Journal of Geology**.

Yours sincerely,

Eduardo Garzanti (on behalf of all co-authors)

Tel: (39) 02 64482088 • Email: eduardo.garzanti@unimib.it

7th January 2022

Figure 1

[Click here to access/download;Figure;Figure 1 Zambezi2 Geography.jpg](#)

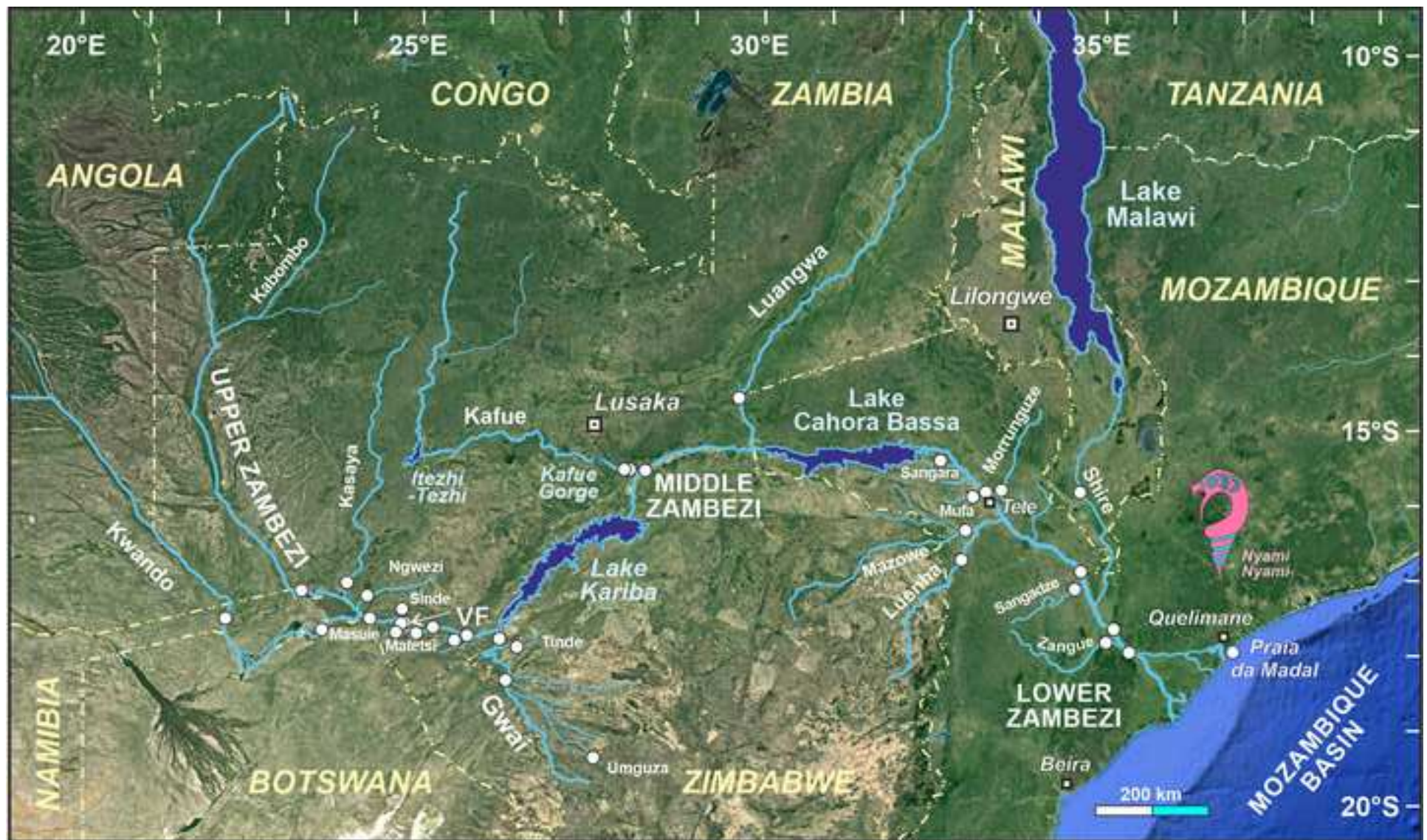


Figure 2

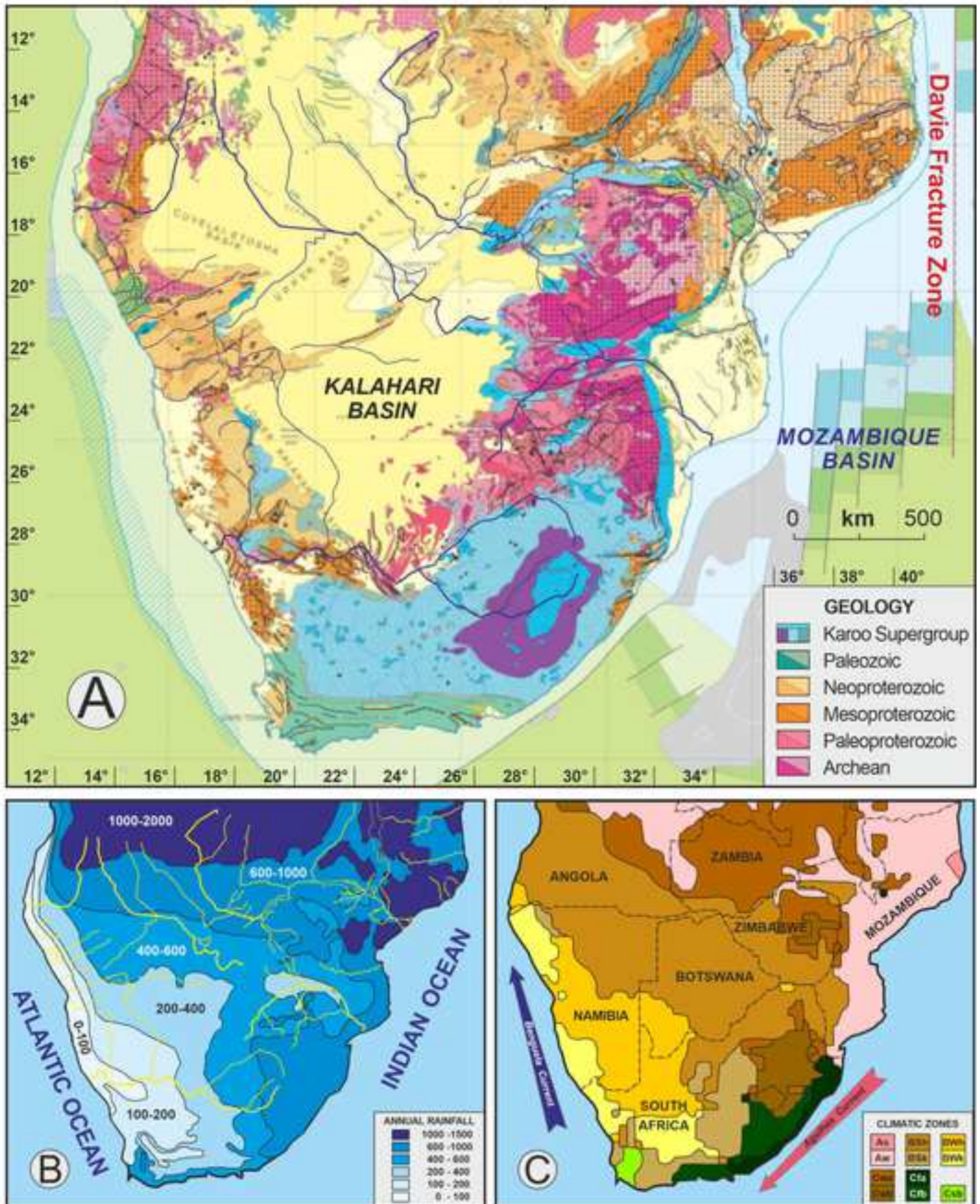
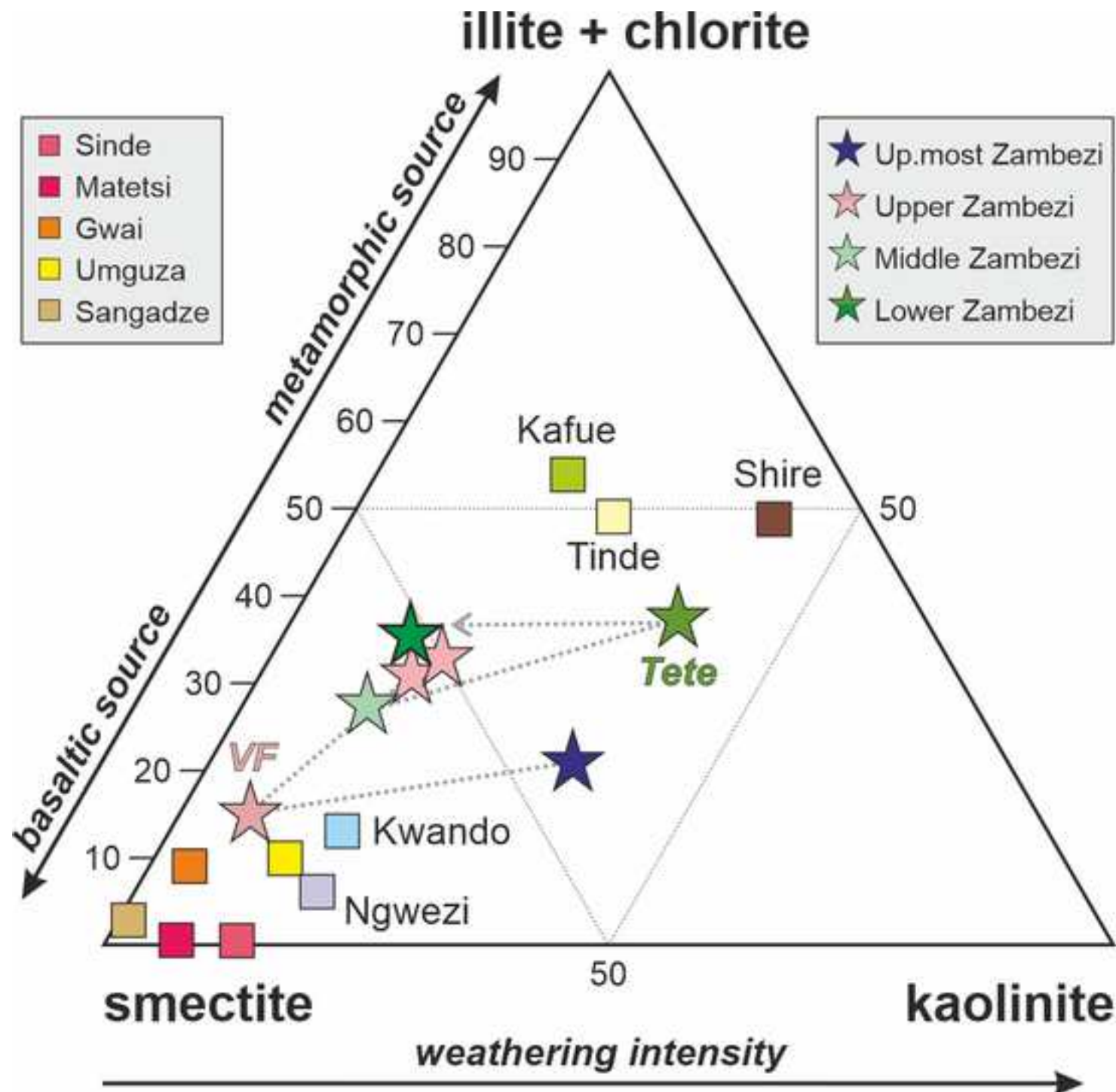


Figure 3



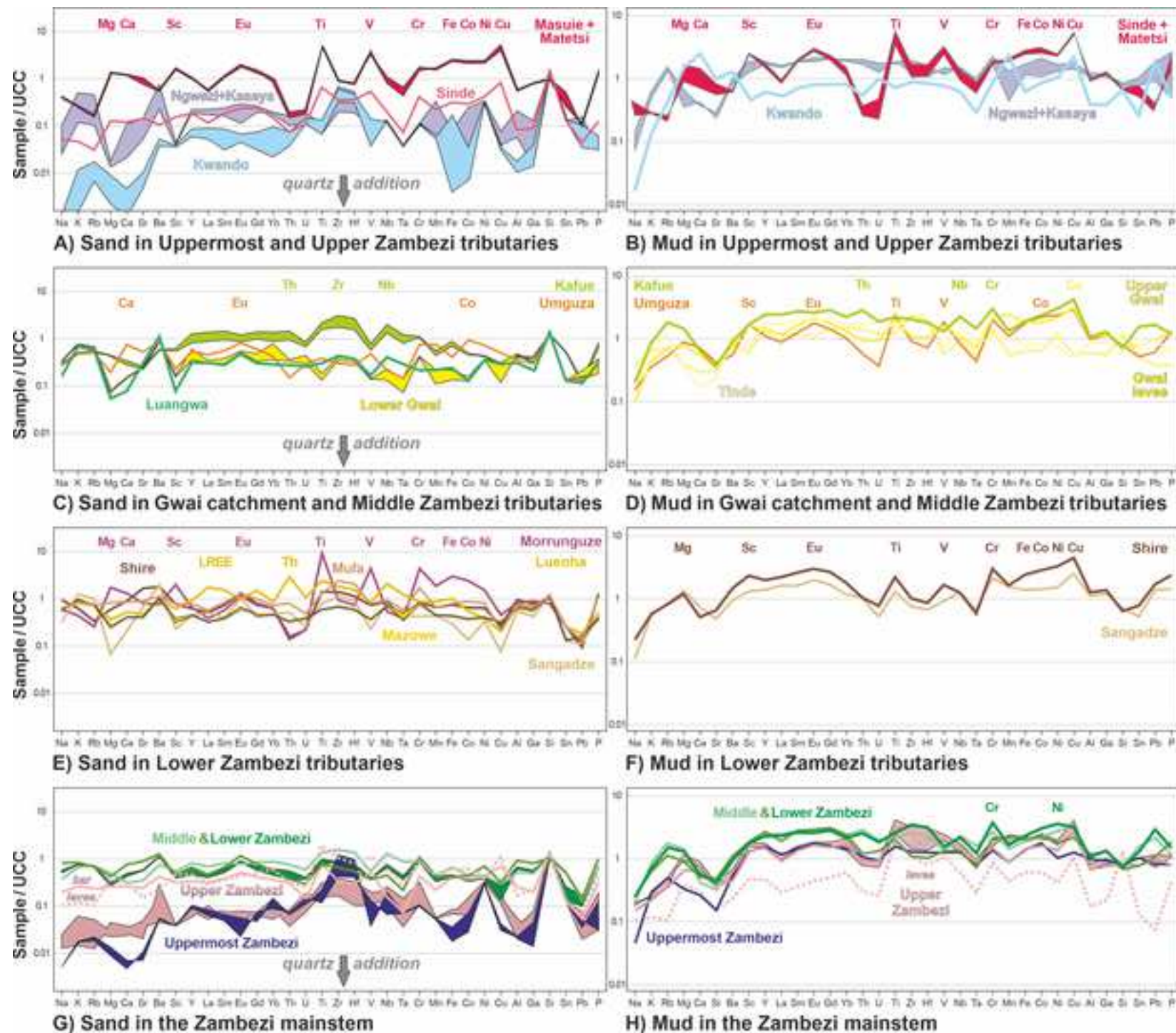


Figure 5

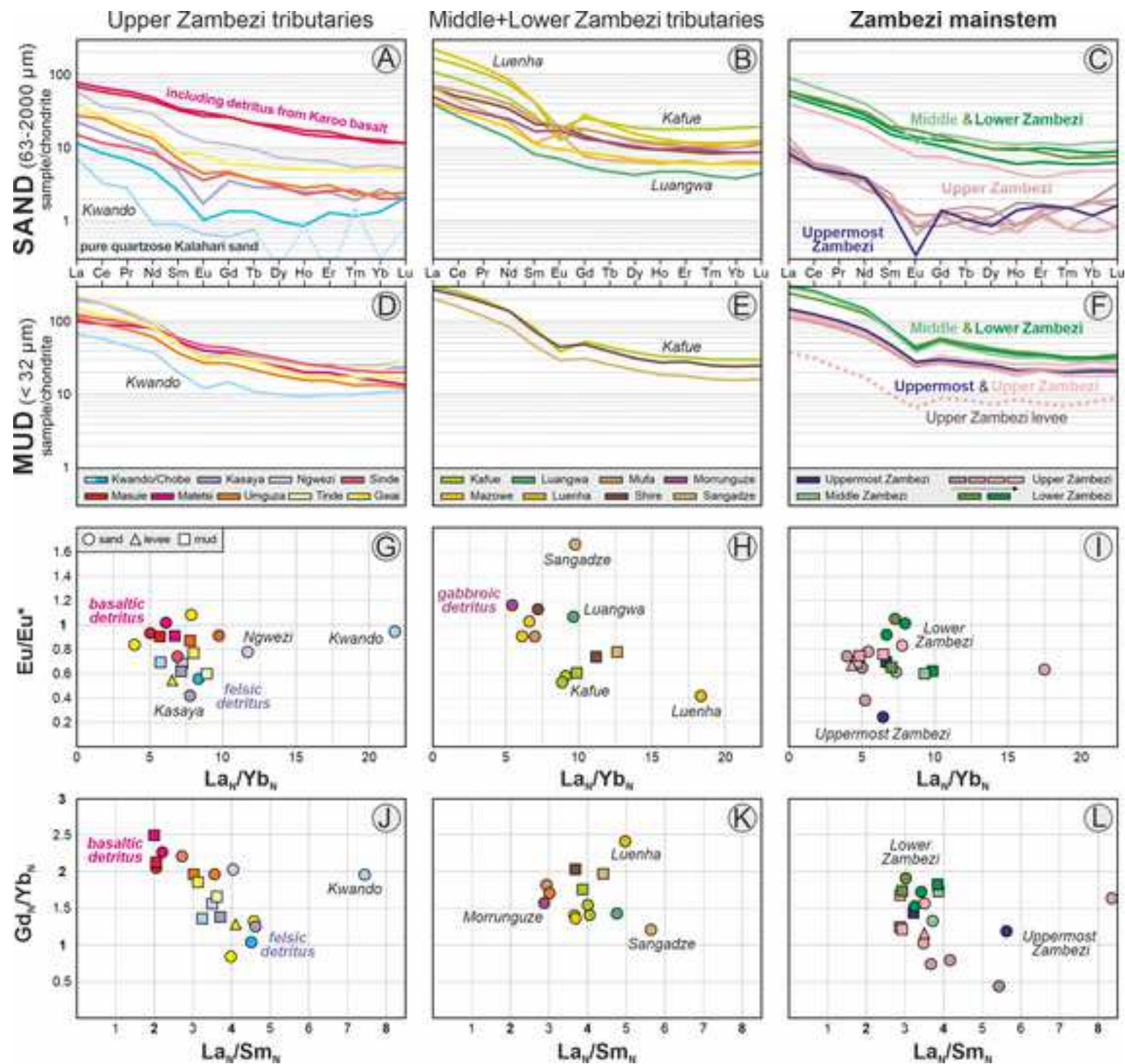
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Figure 6

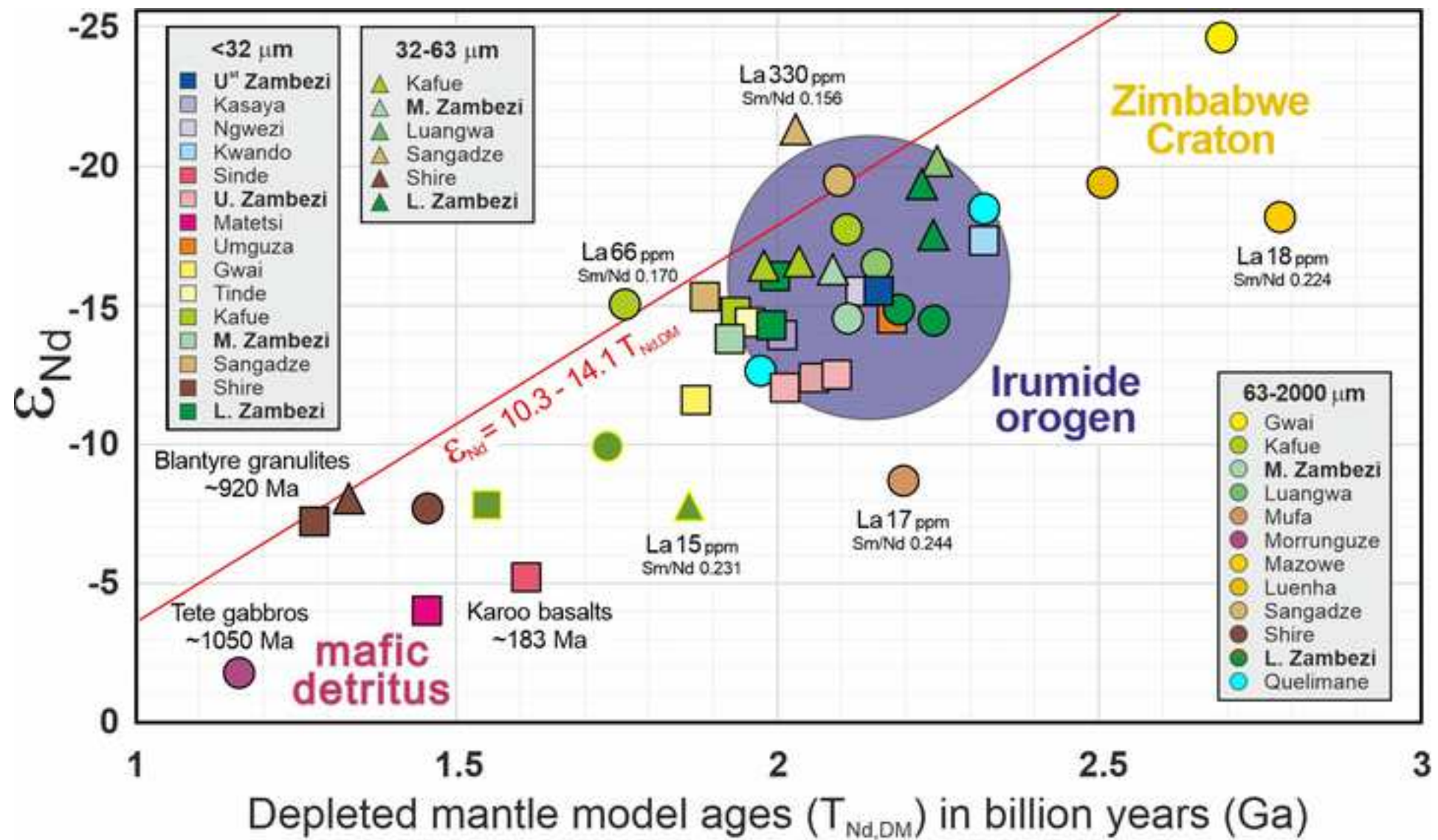


Figure 7

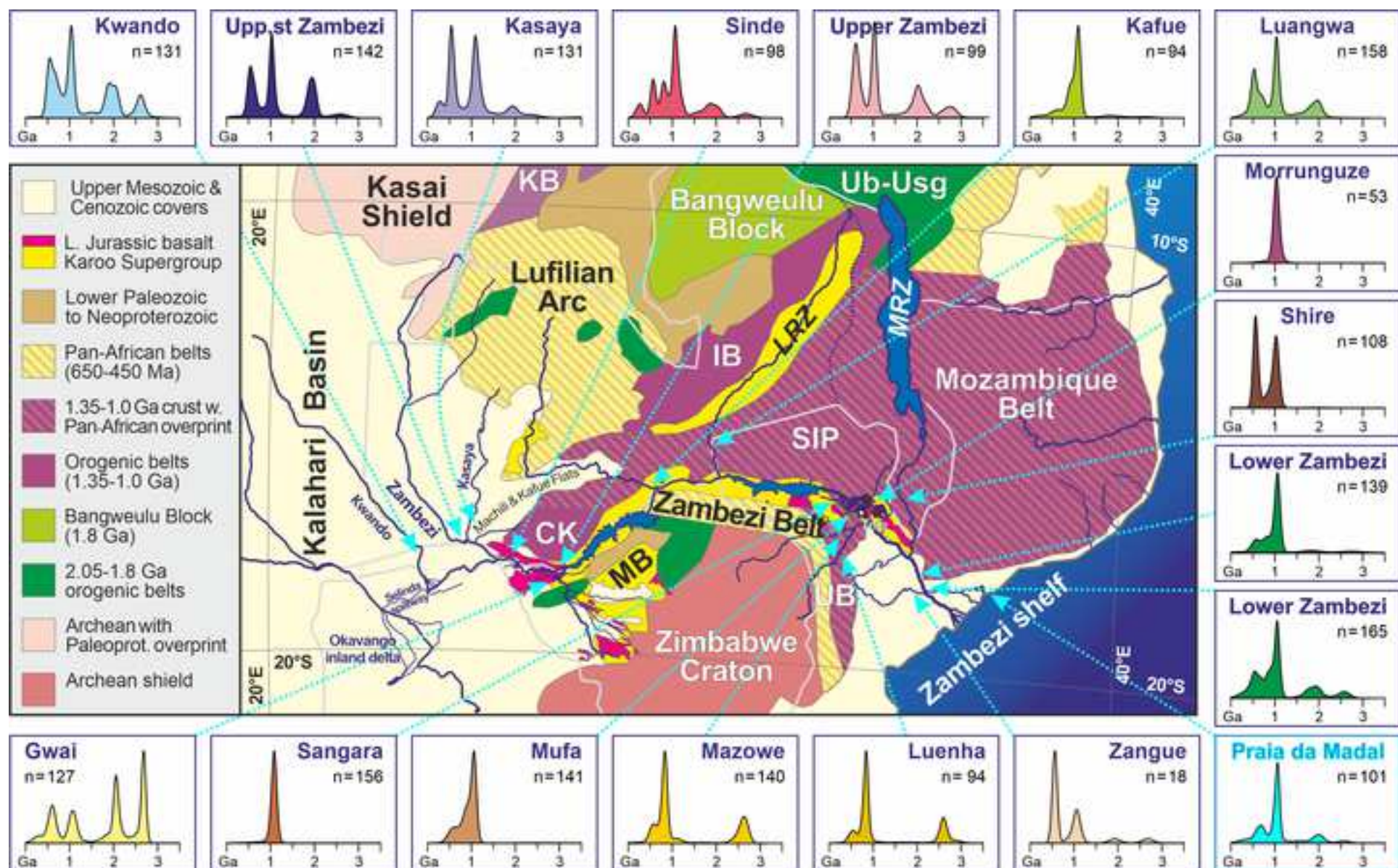
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Figure 8

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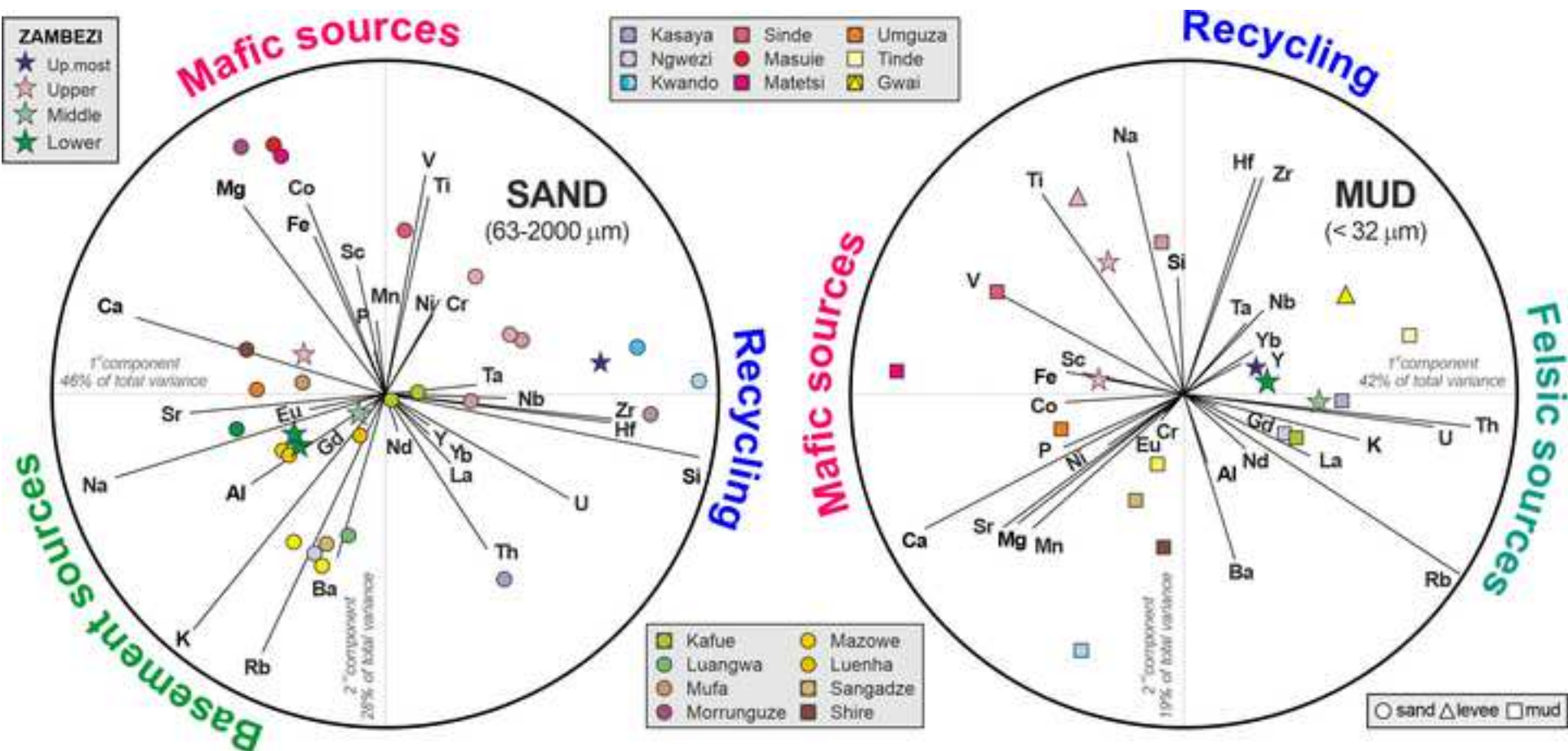


Figure 9

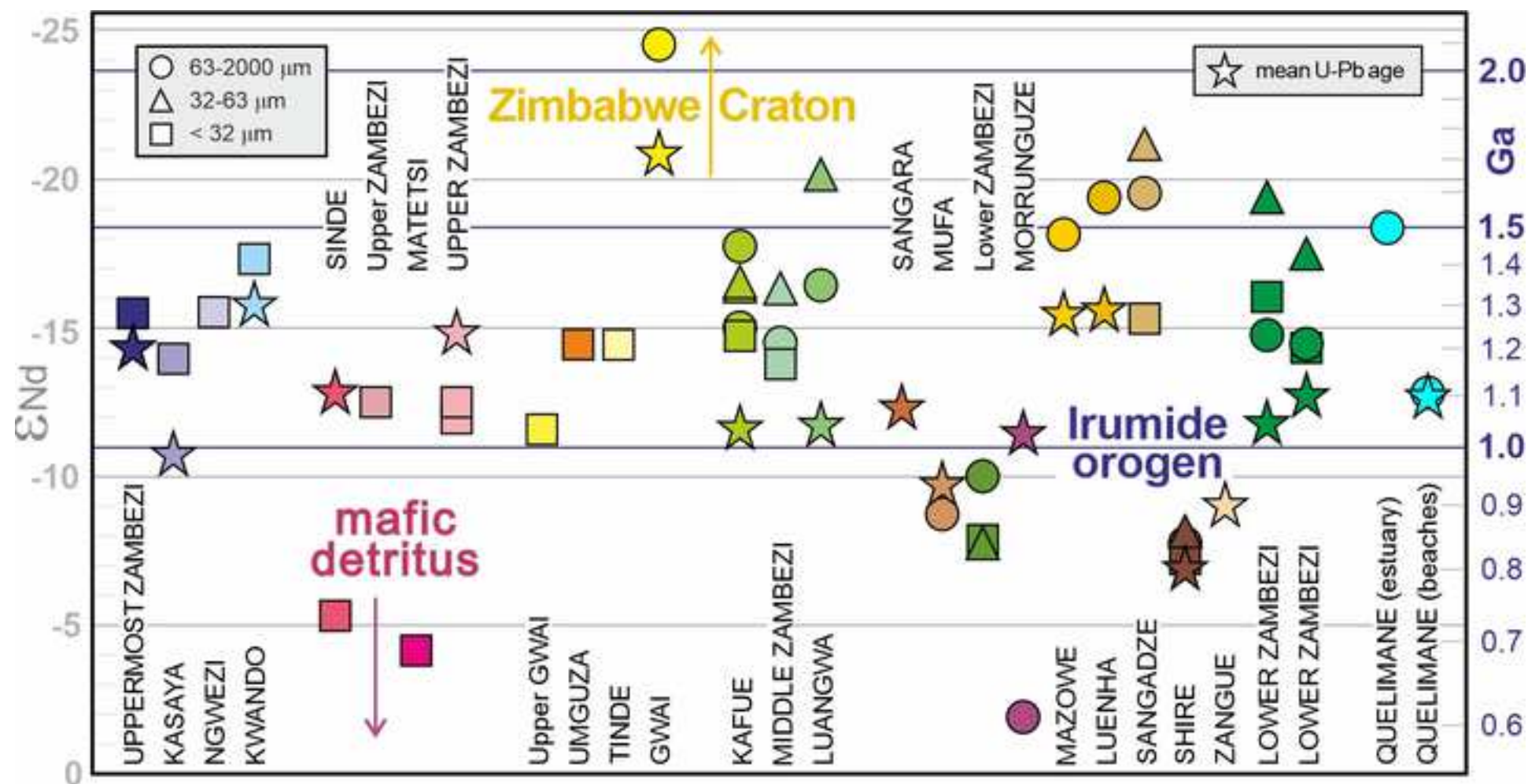


Figure 10

[Click here to access/download;Figure;Figure 10 Zambezi2 MDS.jpg](#)

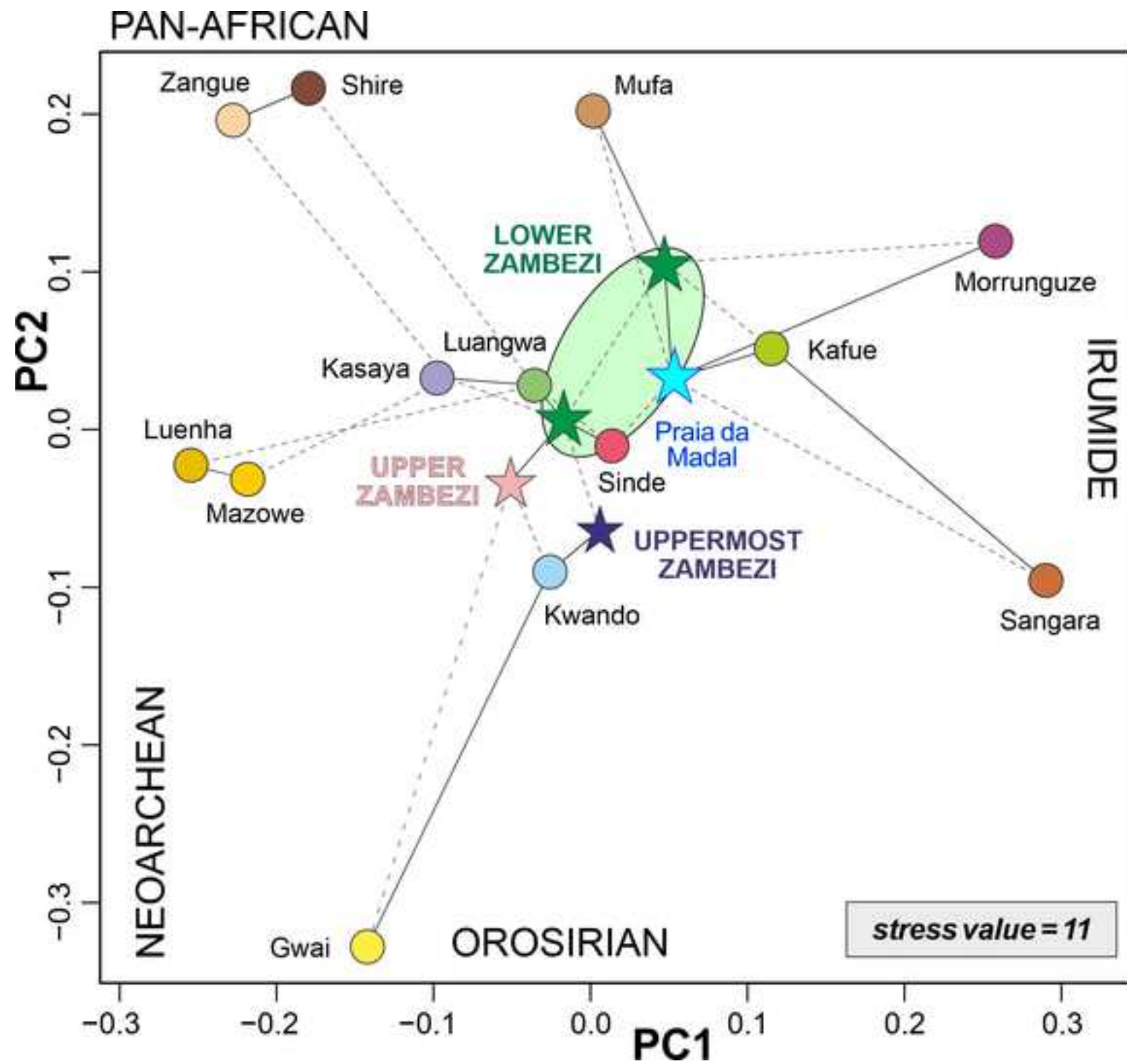


Figure 11

[Click here to access/download;Figure;Figure 11 Zambezi2 CHI Four Panels.jpg](#)

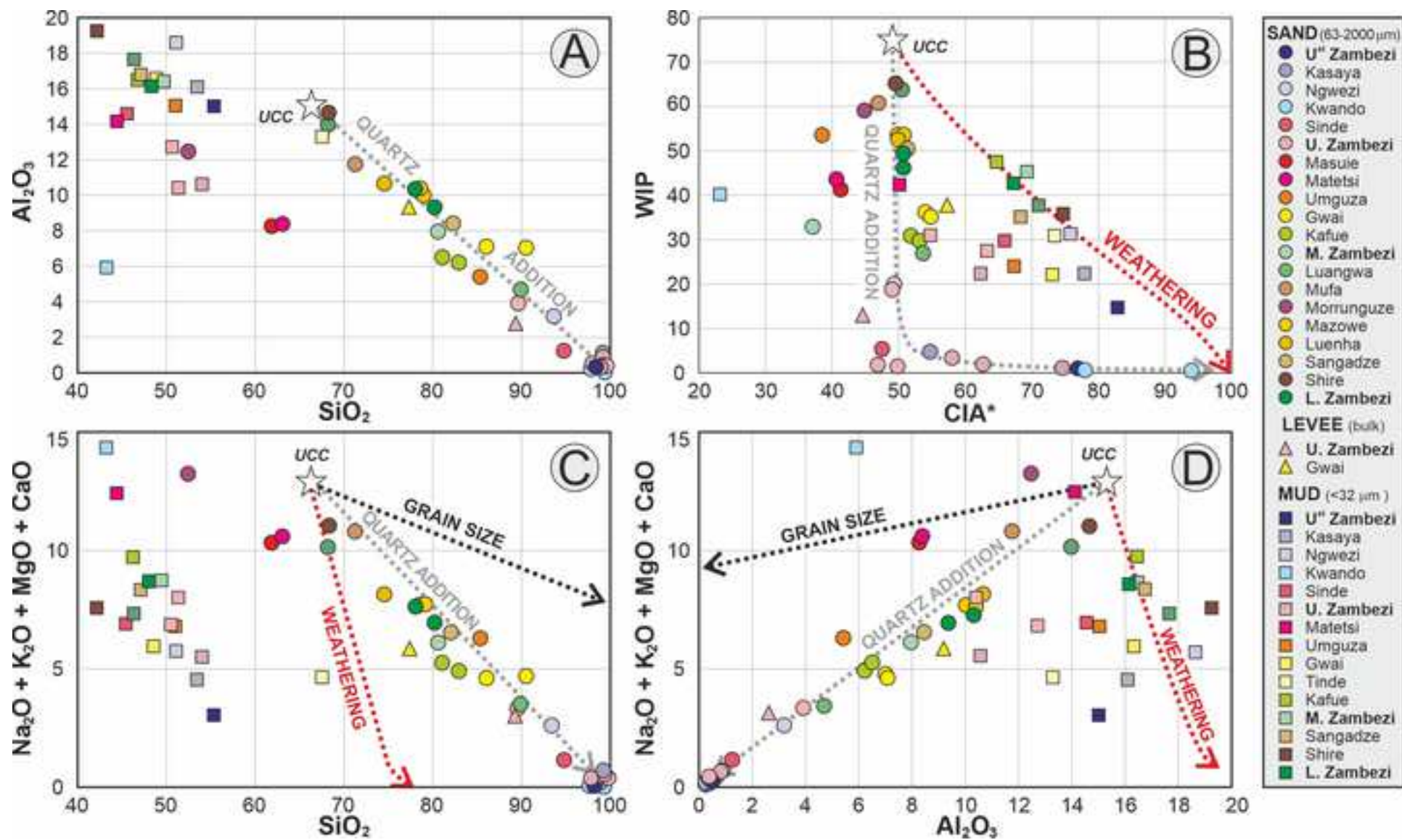


Table 1

| River | BULK SAMPLE (< 32 µm fraction, wet sieved) | | | | | | | | CLAY MINERALS (< 2 µm) | | | | | Kao / (Ill+Chl) |
|-------------------|--|----|----|------|-----|-----|-------|-------|------------------------|-----|-----|-----|-------|--------------------|
| | Qz | KF | Pl | Carb | Amp | Hem | Phyll | total | Sme | Ill | Chl | Kao | total | |
| Uppermost Zambezi | 49 | 15 | 1 | 0 | 0 | 0 | 35 | 100.0 | 43 | 21 | 0 | 36 | 100.0 | 1.7 |
| Ngwezi | 33 | 11 | 6 | 0 | 0 | 0 | 50 | 100.0 | 76 | 6 | 0 | 18 | 100.0 | 3.0 |
| Kwando | 89 | 0 | 0 | 4 | 0 | 0 | 7 | 100.0 | 70 | 13 | 0 | 17 | 100.0 | 1.3 |
| Sinde | 14 | 6 | 17 | 0 | 0 | 10 | 53 | 100.0 | 87 | 0 | 0 | 13 | 100.0 | ∞ |
| Zambezi @ V.Falls | 75 | 8 | 2 | 0 | 0 | 0 | 15 | 100.0 | 78 | 15 | 0 | 7 | 100.0 | 0.5 |
| Matetsi | 7 | 20 | 15 | 4 | 0 | 9 | 45 | 100.0 | 93 | 0 | 0 | 7 | 100.0 | ∞ |
| Upper Zambezi | 41 | 12 | 15 | 0 | 0 | 5 | 27 | 100.0 | 54 | 31 | 0 | 15 | 100.0 | 0.5 |
| Upper Zambezi | 43 | 11 | 19 | 0 | 0 | 4 | 23 | 100.0 | 50 | 33 | 0 | 17 | 100.0 | 0.5 |
| Umgua | 26 | 8 | 7 | 3 | 0 | 0 | 56 | 100.0 | 87 | 4 | 5 | 4 | 100.0 | 0.4 |
| Upper Gwai | 20 | 4 | 4 | 3 | 0 | 0 | 69 | 100.0 | 77 | 5 | 5 | 13 | 100.0 | 1.3 |
| Tinde | 34 | 24 | 5 | 0 | 0 | 0 | 37 | 100.0 | 25 | 40 | 9 | 26 | 100.0 | 0.5 |
| Kafue | 9 | 7 | 11 | 2 | 2 | 1 | 69 | 100.0 | 27 | 54 | 0.5 | 19 | 100.0 | 0.3 |
| Middle Zambezi | 10 | 7 | 11 | 6 | 1 | 0.2 | 64 | 100.0 | 60 | 27 | 0 | 12 | 100.0 | 0.4 |
| Zambezi @ Tete | 19 | 5 | 19 | 0 | 2 | 0 | 54 | 100.0 | 25 | 37 | 0 | 38 | 100.0 | 1.0 |
| Sangadze | 12 | 8 | 10 | 3 | 0.1 | 0 | 67 | 100.0 | 96 | 3 | 0 | 1 | 100.0 | 0.4 |
| Shire | 14 | 7 | 16 | 0 | 2 | 0 | 61 | 100.0 | 9 | 49 | 0 | 42 | 100.0 | 0.9 |
| Lower Zambezi | 17 | 14 | 20 | 0 | 0 | 0 | 49 | 100.0 | 52 | 35 | 0 | 12 | 100.0 | 0.4 |

Table 2

| River | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | MgO | CaO | Na ₂ O | K ₂ O | TiO ₂ | P ₂ O ₅ | MnO | LOI | Rb | Sr | Ba | Sc | Y | Th | Zr | Hf | V | Nb | Cr | Ni | CIA* | α ^{Al} Mg | α ^{Al} Ca | α ^{Al} Na | α ^{Al} K | α ^{Al} Rb | α ^{Al} Sr | α ^{Al} Ba | | | |
|--------------------------|------------------|--------------------------------|--------------------------------|-------|-------|-------------------|------------------|------------------|-------------------------------|-------|------|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|--------------------|--------------------|--------------------|-------------------|--------------------|--------------------|--------------------|--|--|--|
| SAND (63-2000 μm) | wt% | wt% | wt% | wt% | wt% | wt% | wt% | wt% | wt% | wt% | wt% | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | | WEATHERING INDICES | | | | | | | | | |
| Uppermost Zambezi | 98.5 | 0.4 | 0.2 | 0.03 | 0.03 | 0.02 | 0.06 | 0.07 | 0.02 | <0.01 | 0.8 | 2 | 3 | 29 | <1 | 2 | 0.8 | 81 | 2 | 14 | 1 | <14 | <20 | 77 | 1.8 | 3.0 | 4.1 | 1.2 | 1.0 | 3.1 | 0.5 | | | |
| Kasaya | 99.2 | 0.9 | 0.1 | 0.03 | 0.1 | 0.1 | 0.4 | 0.07 | <0.01 | <0.01 | 0.9 | 11 | 18 | 124 | <1 | 4 | 2 | 128 | 3 | <8 | 2 | <14 | <20 | 55 | 4.5 | 2.5 | 2.1 | 0.4 | 0.5 | 1.1 | 0.3 | | | |
| Ngwezi | 93.4 | 3.2 | 0.4 | 0.04 | 0.5 | 0.4 | 1.7 | 0.04 | <0.01 | 0.03 | 0.5 | 47 | 50 | 419 | <1 | 5 | 1 | 38 | 1 | 11 | 2 | 14 | <20 | 49 | 12.3 | 1.8 | 1.9 | 0.4 | 0.4 | 1.4 | 0.3 | | | |
| Kwando | 99.3 | 0.2 | <0.04 | <0.01 | <0.01 | <0.01 | <0.01 | 0.04 | 0.01 | <0.01 | 0.5 | 1 | 2 | 21 | <1 | 1 | 0.4 | 62 | 2 | <8 | 2 | <14 | <20 | >89 | > 2.3 | > 4.4 | > 4.1 | > 3.6 | 1.4 | 2.1 | 0.3 | | | |
| Chobe | 98.0 | 0.3 | 0.9 | 0.02 | 0.02 | <0.01 | 0.04 | 0.08 | <0.01 | <0.01 | 0.7 | 2 | 4 | 29 | <1 | 2 | 1 | 114 | 3 | 15 | 2 | <14 | <20 | 78 | 2.1 | 3.4 | n.d. | 1.4 | 0.9 | 1.6 | 0.4 | | | |
| Upper Zambezi | 98.9 | 0.3 | 0.1 | 0.02 | 0.02 | 0.02 | 0.06 | 0.1 | <0.01 | <0.01 | 0.9 | 2 | 4 | 31 | <1 | 2 | 1 | 232 | 6 | <8 | 2 | <14 | <20 | 75 | 2.5 | 4.2 | 3.9 | 1.1 | 1.1 | 1.9 | 0.4 | | | |
| Sinde | 94.8 | 1.3 | 1.6 | 0.3 | 0.5 | 0.2 | 0.2 | 0.4 | 0.02 | 0.02 | 0.9 | 3 | 51 | 58 | 2 | 4 | 1 | 68 | 2 | 57 | 2 | 27 | <20 | 47 | 0.7 | 0.6 | 1.5 | 1.6 | 2.5 | 0.5 | 0.8 | | | |
| Zambezi up.Vic.Falls | 98.0 | 0.6 | 0.4 | 0.05 | 0.1 | 0.06 | 0.1 | 0.2 | 0.03 | <0.01 | 0.6 | 3 | 11 | 52 | <1 | 2 | 1 | 73 | 2 | 21 | 3 | 14 | <20 | 63 | 1.7 | 1.4 | 2.1 | 1.0 | 1.2 | 1.1 | 0.4 | | | |
| Zambezi rapid #9 | 99.2 | 0.8 | 0.3 | 0.07 | 0.1 | 0.1 | 0.2 | 0.2 | <0.01 | <0.01 | 0.8 | 5 | 18 | 81 | <1 | 2 | 1 | 62 | 2 | 14 | 3 | <14 | <20 | 58 | 1.9 | 1.6 | 2.0 | 0.8 | 1.0 | 1.1 | 0.4 | | | |
| Zambezi rapid #19 | 99.4 | 0.3 | 0.3 | 0.07 | 0.1 | 0.05 | 0.05 | 0.1 | <0.01 | <0.01 | 1.0 | 2 | 7 | 157 | <1 | 1 | 1 | 31 | 1 | 11 | 2 | 21 | <20 | 50 | 0.7 | 0.7 | 1.5 | 1.3 | 1.2 | 1.0 | 0.1 | | | |
| Masuie | 61.8 | 8.3 | 12.9 | 3.1 | 4.9 | 1.5 | 0.9 | 2.8 | 0.19 | 0.15 | 2.4 | 18 | 268 | 295 | 22 | 23 | 2 | 168 | 4 | 414 | 10 | 96 | 78 | 41 | 0.4 | 0.4 | 1.3 | 1.9 | 2.9 | 0.7 | 1.1 | | | |
| Upper Zambezi | 99.7 | 0.4 | 0.4 | 0.1 | 0.2 | 0.06 | 0.05 | 0.1 | <0.01 | <0.01 | 0.8 | 1 | 13 | 25 | <1 | 2 | 0 | 37 | 1 | 16 | 1 | <14 | <20 | 47 | 0.6 | 0.6 | 1.4 | 1.5 | 1.8 | 0.6 | 0.6 | | | |
| Matetsi | 63.1 | 8.4 | 11.7 | 3.1 | 5.0 | 1.7 | 0.8 | 2.8 | 0.23 | 0.14 | 2.9 | 16 | 365 | 296 | 20 | 22 | 2 | 182 | 5 | 356 | 13 | 109 | 70 | 41 | 0.4 | 0.4 | 1.2 | 2.0 | 3.4 | 0.5 | 1.1 | | | |
| Zambezi up. Kariba | 89.7 | 3.9 | 2.0 | 0.6 | 1.1 | 0.8 | 0.9 | 0.5 | 0.05 | 0.02 | 0.5 | 24 | 85 | 235 | 4 | 7 | 3 | 65 | 2 | 57 | 2 | 27 | <20 | 49 | 1.1 | 0.9 | 1.2 | 0.9 | 1.0 | 1.0 | 0.6 | | | |
| Umgua | 85.4 | 5.4 | 2.0 | 0.4 | 3.2 | 1.1 | 1.6 | 0.2 | 0.03 | 0.07 | 3.2 | 52 | 186 | 476 | 3 | 12 | 2 | 57 | 2 | 51 | 3 | 48 | 24 | 37 | 1.9 | 0.4 | 1.2 | 0.7 | 0.7 | 0.6 | 0.4 | | | |
| Lower Gwai | 88.3 | 7.1 | 0.9 | 0.2 | 0.6 | 1.3 | 2.6 | 0.1 | 0.05 | 0.02 | 0.9 | 69 | 87 | 484 | 2 | 11 | 4 | 72 | 2 | 15 | 2 | 27 | <20 | 54 | 6.2 | 2.9 | 1.4 | 0.6 | 0.7 | 1.8 | 0.5 | | | |
| Kafue (FS) | 83.0 | 6.2 | 3.5 | 1.0 | 1.2 | 1.0 | 1.7 | 0.9 | 0.10 | 0.04 | 1.1 | 58 | 80 | 325 | 7 | 18 | 10 | 334 | 9 | 61 | 16 | 68 | <20 | 53 | 0.9 | 1.5 | 1.5 | 0.8 | 0.7 | 1.8 | 0.7 | | | |
| Kafue (VFS) | 81.1 | 6.5 | 4.4 | 1.0 | 1.5 | 1.2 | 1.6 | 1.3 | 0.13 | 0.05 | 1.0 | 52 | 92 | 316 | 8 | 28 | 16 | 596 | 16 | 84 | 24 | 68 | <20 | 52 | 1.0 | 1.2 | 1.4 | 0.9 | 0.9 | 1.6 | 0.7 | | | |
| Middle Zambezi | 80.6 | 8.0 | 3.3 | 1.1 | 1.3 | 1.5 | 2.3 | 0.8 | 0.11 | 0.04 | 0.9 | 74 | 122 | 415 | 7 | 18 | 8 | 294 | 8 | 58 | 15 | 55 | <20 | 53 | 1.1 | 1.7 | 1.4 | 0.8 | 0.7 | 1.5 | 0.7 | | | |
| Luangwa | 89.9 | 4.7 | 1.2 | 0.1 | 0.3 | 0.6 | 2.4 | 0.2 | 0.05 | 0.02 | 0.3 | 59 | 107 | 620 | 1 | 7 | 3 | 83 | 2 | 18 | 5 | 14 | <20 | 54 | 5.7 | 3.9 | 1.9 | 0.4 | 0.5 | 1.0 | 0.3 | | | |
| Mufa | 71.3 | 11.8 | 3.9 | 1.8 | 3.7 | 2.4 | 2.9 | 0.8 | 0.18 | 0.06 | 0.9 | 76 | 315 | 626 | 10 | 18 | 9 | 459 | 12 | 78 | 11 | 109 | 27 | 47 | 0.9 | 0.9 | 1.3 | 0.9 | 1.0 | 0.9 | 0.7 | | | |
| L.Zambezi @ Tete | 68.2 | 14.0 | 2.1 | 0.9 | 3.2 | 3.2 | 2.8 | 0.5 | 0.16 | 0.04 | 4.8 | 70 | 313 | 695 | 6 | 15 | 4 | 125 | 3 | 39 | 5 | 68 | 23 | 50 | 2.2 | 1.2 | 1.1 | 1.1 | 1.4 | 1.0 | 0.7 | | | |
| Morrunguze | 52.4 | 12.5 | 15.1 | 3.9 | 5.5 | 2.4 | 1.5 | 5.5 | 0.08 | 0.17 | 0.7 | 27 | 285 | 424 | 26 | 15 | 2 | 181 | 4 | 471 | 7 | 281 | 50 | 45 | 0.5 | 0.6 | 1.4 | 1.8 | 3.2 | 1.0 | 1.1 | | | |
| Luenha | 74.5 | 10.7 | 5.1 | 0.8 | 2.2 | 2.4 | 2.8 | 1.4 | 0.08 | 0.08 | -0.3 | 74 | 168 | 552 | 8 | 21 | 32 | 348 | 9 | 89 | 25 | 55 | <20 | 50 | 1.9 | 1.3 | 1.1 | 0.9 | 1.0 | 1.5 | 0.7 | | | |
| Mazowe | 78.7 | 10.2 | 2.2 | 0.6 | 1.7 | 2.2 | 3.3 | 0.4 | 0.07 | 0.04 | 0.5 | 76 | 143 | 560 | 5 | 10 | 4 | 130 | 3 | 39 | 9 | 51 | <20 | 50 | 2.7 | 1.7 | 1.2 | 0.7 | 0.9 | 1.6 | 0.7 | | | |
| Sangadze | 82.1 | 8.5 | 1.5 | 0.2 | 0.9 | 1.3 | 4.2 | 0.5 | 0.07 | 0.04 | 0.6 | 103 | 237 | 1093 | 3 | 10 | 6 | 212 | 5 | 24 | 10 | 27 | <20 | 51 | 8.2 | 2.7 | 1.7 | 0.4 | 0.6 | 0.8 | 0.3 | | | |
| Shire | 68.3 | 14.7 | 3.8 | 1.3 | 3.9 | 3.7 | 2.1 | 0.8 | 0.20 | 0.06 | 0.9 | 35 | 585 | 995 | 10 | 14 | 2 | 268 | 7 | 78 | 11 | 55 | 21 | 50 | 1.6 | 1.0 | 1.0 | 1.5 | 2.9 | 0.6 | 0.5 | | | |
| Lower Zambezi (FS) | 80.2 | 9.3 | 2.1 | 0.6 | 1.8 | 2.0 | 2.6 | 0.5 | 0.10 | 0.03 | 0.7 | 67 | 199 | 621 | 5 | 10 | 4 | 165 | 5 | 40 | 8 | 55 | <20 | 51 | 2.3 | 1.4 | 1.2 | 0.8 | 0.9 | 1.1 | 0.5 | | | |
| Lower Zambezi (VFS) | 78.1 | 10.4 | 2.3 | 0.7 | 2.1 | 2.3 | 2.6 | 0.6 | 0.11 | 0.04 | 0.7 | 69 | 200 | 616 | 6 | 15 | 6 | 153 | 4 | 41 | 9 | 68 | <20 | 51 | 2.1 | 1.4 | 1.2 | 0.9 | 1.0 | 1.2 | 0.6 | | | |
| MUD (<32 μm) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Uppermost Zambezi | 55.4 | 15.0 | 7.0 | 0.7 | 1.1 | 0.2 | 1.0 | 0.9 | 0.13 | 0.08 | 18 | 53 | 54 | 301 | 17 | 34 | 11 | 246 | 8 | 134 | 15 | 89 | 34 | 83 | 2.9 | 3.7 | 21.4 | 3.3 | 1.9 | 6.4 | 1.8 | | | |
| Kasaya | 53.5 | 16.1 | 5.8 | 0.8 | 1.8 | 0.3 | 1.7 | 1.0 | 0.41 | 0.04 | n.d. | 147 | 84 | 459 | 16 | 37 | 22 | 372 | 9 | 122 | 19 | 109 | 43 | 78 | 3.0 | 2.5 | 14.2 | 2.1 | 0.7 | 4.4 | 1.3 | | | |
| Ngwezi | 51.1 | 18.6 | 8.5 | 1.5 | 1.6 | 0.6 | 2.1 | 1.1 | 0.08 | 0.12 | 15 | 163 | 101 | 555 | 24 | 41 | 18 | 232 | 6 | 157 | 17 | 144 | 55 | 76 | 1.8 | 3.3 | 8.2 | 1.9 | 0.8 | 4.2 | 1.2 | | | |
| Kwando | 43.3 | 5.9 | 3.1 | 3.3 | 10.6 | 0.07 | 0.5 | 0.4 | 0.08 | 0.21 | 30 | 44 | 339 | 707 | 6 | 14 | 6 | 170 | 5 | 82 | 8 | 55 | 34 | 23 | 0.3 | 0.2 | 21.7 | 2.9 | 0.9 | 0.4 | 0.3 | | | |
| Sinde | 45.5 | 14.6 | 14.2 | 2.0 | 3.0 | 1.0 | 0.9 | 3.5 | 0.22 | 0.18 | 15 | 26 | 194 | 362 | 32 | 40 | 4 | 321 | 10 | 348 | 17 | 123 | 81 | 66 | 1.1 | 1.4 | 3.7 | 3.4 | 3.8 | 1.7 | 1.5 | | | |
| Zambezi up.Vic.Falls | 54.0 | 10.6 | 7.3 | 1.4 | 2.7 | 0.6 | 0.8 | 1.8 | 0.13 | 0.08 | 20 | 37 | 125 | 251 | 18 | 32 | 10 | 623 | 19 | 171 | 19 | 96 | 45 | 62 | 1.1 | 1.1 | 4.6 | 3.1 | 1.9 | 2.0 | 1.5 | | | |
| Matetsi | 44.4 | 14.2 | 12.2 | 3.7 | 6.2 | 1.7 | 0.9 | 2.0 | 0.39 | 0.17 | 14 | 22 | 291 | 332 | 31 | 33 | 3 | 201 | 6 | 259 | 11 | 109 | 74 | 50 | 0.6 | 0.6 | 2.2 | 3.3 | 4.4 | 1.1 | 1.5 | | | |
| Zambezi up. Kariba | 50.7 | 12.7 | 10.1 | 2.1 | 3.1 | 0.7 | 0.9 | 1.5 | 0.17 | 0.22 | 18 | 51 | 137 | 374 | 21 | 33 | 9 | 274 | 8 | 211 | 15 | 103 | 55 | 63 | 0.9 | 1.1 | 4.6 | 3.1 | 1.7 | 2.1 | 1.2 | | | |
| Zambezi up. Kariba | 51.4 | 10.4 | 10.3 | 2.6 | 3.8 | 0.8 | 0.8 | 2.5 | 0.18 | 0.16 | 17 | 39 | 134 | 262 | 23 | 39 | 12 | 627 | 18 | 258 | 21 | 130 | 64 | 55 | 0.6 | 0.8 | 3.3 | 2.8 | 1.8 | 1.8 | 1.4 | | | |
| Umgua | 51.0 | 15.0 | 8.8 | 2.0 | 3.0 | 0.6 | 1.2 | 1.4 | 0.21 | 0.10 | 16 | 55 | 147 | 303 | 22 | 25 | 6 | 175 | 4 | 196 | 10 | 137 | 77 | 67 | 1.1 | 1.4 | 6.4 | 2.8 | 1.9 | 2.4 | 1.8 | | | |
| Upper Gwai | 48.6 | 16.3 | 8.9 | 1.7 | 2.3 | 0.4 | 1.5 | 1.2 | 0.20 | 0.22 | 18 | 75 | 125 | 410 | 22 | 30 | 10 | 200 | 6 | 174 | 13 | 137 | 70 | 73 | 1.4 | 1.9 | 10.5 | 2.4 | 1.5 | 3.0 | 1.4 | | | |
| Tinde | 67.5 | 13.3 | 4.0 | 0.8 | 0.7 | 0.7 | 2.5 | 0.9 | 0.09 | 0.10 | 9 | 119 | 83 | 607 | 10 | 39 | 18 | 466 | 14 | 73 | 19 | 62 | 25 | 73 | 2.4 | 5.2 | 5.2 | 1.2 | 0.8 | 3.7 | 0.8 | | | |
| Kafue (VFS) | 46.8 | 16.5 | 9.5 | 3.2 | 2.7 | 0.8 | 2.9 | 1.3 | 0.19 | 0.12 | 15 | 188 | 125 | 497 | 22 | 54 | 30 | 389 | 11 | 139 | 27 | 192 | 99 | 65 | 0.7 | 1.7 | 5.3 | 1.3 | 0.6 | 3.0 | 1.2 | | | |
| Middle Zambezi | 49.5 | 16.4 | 9.5 | 3.2 | 1.8 | 0.8 | 2.9 | 1.3 | 0.19 | 0.13 | 14 | 184 | 113 | 512 | 22 | 57 | 31 | 489 | 13 | 144 | 28 | 171 | 91 | 69 | 0.7 | 2.6 | 5.0 | 1.3 | 0.6 | 3.4 | 1.2 | | | |
| L.Zambezi @ Tete | 46.4 | 17.7 | 10.4 | 2.0 | 2.2 | 1.0 | 2.1 | 1.2 | 0.30 | 0.20 | 16 | 118 | 170 | 614 | 24 | 59 | 13 | 210 | 6 | 142 | 16 | 137 | 59 | 71 | 1.3 | 2.3 | 4.4 | 1.8 | 1.0 | 2.4 | 1.0 | | | |
| Sangadze | 47.1 | 16.8 | 6.9 | 3.0 | 3.1 | 0.4 | 1.9 | 0.8 | 0.23 | 0.14 | 19 | 86 | 166 | 523 | 17 | 30 | 11 | 144 | 4 | 98 | 15 | 137 | 50 | 68 | 0.8 | 1.5 | 9.8 | 2.0 | 1.3 | 2.3 | 1.2 | | | |
| Shire | 42.2 | 19.3 | 12.1 | 2.6 | 2.2 | 0.9 | 1.9 | 1.3 | 0.38 | 0.15 | 17 | 84 | 231 | 807 | | | | | | | | | | | | | | | | | | | | |

Table 3

| River | ϵ_{Nd} | | | t_{DM} (Ma) | | |
|----------------------|-----------------|---------------|-----------------|---------------|---------------|-----------------|
| | <32 μm | 32-63 μm | 63-2000 μm | <32 μm | 32-63 μm | 63-2000 μm |
| Uppermost Zambezi* | -15.5 | n.d. | n.d. | 2162 | n.d. | n.d. |
| Kasaya* | -14.0 | n.d. | n.d. | 2006 | n.d. | n.d. |
| Ngwezi* | -15.6 | n.d. | n.d. | 2128 | n.d. | n.d. |
| Kwando* | -17.3 | n.d. | n.d. | 2320 | n.d. | n.d. |
| Sinde* | -5.3 | n.d. | n.d. | 1608 | n.d. | n.d. |
| Zambezi @ Vic.Falls* | -12.5 | n.d. | n.d. | 2056 | n.d. | n.d. |
| Matetsi* | -4.1 | n.d. | n.d. | 1454 | n.d. | n.d. |
| Upper Zambezi* | -12.0 | n.d. | n.d. | 2010 | n.d. | n.d. |
| Upper Zambezi* | -12.5 | n.d. | n.d. | 2092 | n.d. | n.d. |
| Umguzi* | -14.7 | n.d. | n.d. | 2177 | n.d. | n.d. |
| Upper Gwai* | -11.6 | n.d. | n.d. | 1872 | n.d. | n.d. |
| Tinde* | -14.4 | n.d. | n.d. | 1953 | n.d. | n.d. |
| Gwai | n.d. | n.d. | -24.6 | n.d. | n.d. | 2690 |
| Kafue (FS) | n.d. | -16.5 | -17.7 | n.d. | 2029 | 2107 |
| Kafue (VFS) | -14.8 | -16.4 | -15.0 | 1935 | 1976 | 1762 |
| Middle Zambezi | -13.8 | -16.2 | -14.5 | 1925 | 2084 | 2106 |
| Luangwa | n.d. | -20.1 | -16.5 | n.d. | 2244 | 2155 |
| Mufa | n.d. | n.d. | -8.8 | n.d. | n.d. | 2195 |
| L.Zambezi @ Tete° | -7.8 | -7.7 | -10.0 | 1552 | 1864 | 1735 |
| Morrunguze | n.d. | n.d. | -1.9 | n.d. | n.d. | 1162 |
| Mazowe | n.d. | n.d. | -18.2 | n.d. | n.d. | 2781 |
| Luenha | n.d. | n.d. | -19.4 | n.d. | n.d. | 2504 |
| Sangadze | -15.3 | -21.1 | -19.5 | 1887 | 2028 | 2094 |
| Shire | -7.3 | -8.0 | -7.7 | 1279 | 1333 | 1455 |
| Lower Zambezi (FS) | -16.0 | -19.3 | -14.8 | 1995 | 2221 | 2188 |
| Lower Zambezi (VFS) | -14.3 | -17.4 | -14.5 | 1990 | 2242 | 2242 |
| Quelimane (estuary) | n.d. | n.d. | -18.3 | n.d. | n.d. | 2319 |
| Quelimane (beach) | n.d. | n.d. | -12.7 | n.d. | n.d. | 1968 |

Table 4

| River | Karoo | | Pan-African II | | Pan-African I | | Irumide | | Lukamfwa | | Eburnean | | Limpopo | |
|-------------------|----------|----|----------------|-----|---------------|-----|-----------|------|-----------|----|------------|-----|------------|-----|
| Uppermost Zambezi | 235 ± 14 | 2% | 561 ± 10 | 27% | | | 1009 ± 15 | 39% | | | 1989 ± 31 | 32% | | |
| Kasaya | 281 ± 12 | 8% | 558 ± 10 | 34% | | | 1100 ± 16 | 45% | | | 2064 ± 58 | 13% | | |
| Kwando | | | 575 ± 11 | 27% | | | 990 ± 17 | 36% | | | 1891 ± 36 | 25% | 2571 ± 78 | 12% |
| Sinde | 255 ± 9 | 7% | 570 ± 16 | 15% | 816 ± 30 | 15% | 1079 ± 21 | 42% | | | 1968 ± 46 | 21% | | |
| Upper Zambezi | | | 593 ± 11 | 33% | | | 987 ± 20 | 34% | | | 1905 ± 46 | 24% | 2578 ± 103 | 9% |
| Gwai | 243 ± 11 | 4% | 589 ± 12 | 19% | | | 1064 ± 23 | 17% | | | 2028 ± 40 | 29% | 2606 ± 52 | 31% |
| Kafue | 230 ± 13 | 3% | 616 ± 22 | 11% | | | 1035 ± 12 | 79% | | | 1866 ± 87 | 5% | 2579 ± 205 | 2% |
| Luangwa | | | 550 ± 15 | 20% | 717 ± 39 | 8% | 1066 ± 17 | 54% | 1530 ± 76 | 8% | 1998 ± 82 | 10% | | |
| Sangara | | | | | | | 1061 ± 8 | 100% | | | | | | |
| Mufa | | | 559 ± 19 | 13% | 754 ± 50 | 12% | 1002 ± 14 | 75% | | | | | | |
| Morrunguze | | | | | | | 1030 ± 18 | 100% | | | | | | |
| Mazowe | | | 555 ± 14 | 14% | 844 ± 10 | 57% | | | | | | | 2518 ± 41 | 29% |
| Luenha | | | 529 ± 18 | 12% | 831 ± 12 | 58% | | | | | | | 2529 ± 49 | 30% |
| Shire | | | 564 ± 8 | 46% | | | 1022 ± 13 | 54% | | | | | | |
| Zangue | | | 560 ± 18 | 55% | | | 1036 ± 42 | 33% | | | 1926 ± 197 | 6% | 2676 ± 274 | 6% |
| Lower Zambezi | | | 597 ± 15 | 17% | | | 1013 ± 11 | 72% | | | 1851 ± 82 | 6% | 2522 ± 91 | 5% |
| Lower Zambezi | | | 587 ± 11 | 21% | | | 1039 ± 12 | 49% | | | 1878 ± 35 | 22% | 2545 ± 42 | 8% |
| Praia da Madal | 272 ± 14 | 4% | | | 686 ± 27 | 21% | 1044 ± 15 | 56% | | | 1998 ± 53 | 17% | 2558 ± 72 | 2% |