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On the Antiquity of the Zambezi River, its Rifts, and its Wilderness

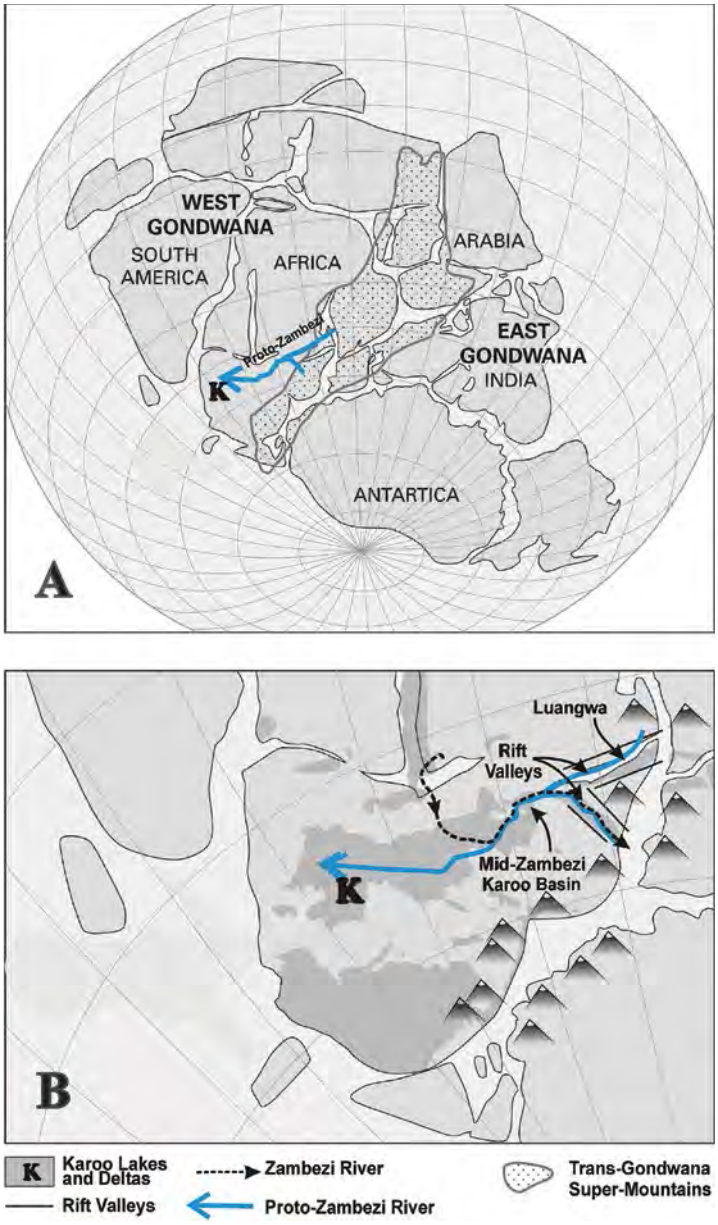
Ancient Rivers

Africa's Zambezi is now established as Earth's oldest known river – the direct descendent of an ancient Proto-Zambezi river. The origins of the Zambezi have been deciphered from geological evidence across the vast wilderness of the Chicoa, Gwembe, Luangwa, Mana and Sebungwe valleys of south-central Africa; here, rock formations and landforms preserve the central repository of the river's history back into the Palaeozoic Era before 280 million years ago. The Proto-Zambezi river originated in the drainage system that was established as vast Dwyka ice-sheets were receding across the super-continent of Gondwana. At this time the immense highlands of the Trans-Gondwana mountains directed the westerly flow of glacial meltwaters into the interior of Gondwana. With its catchment entirely contained within Gondwana, this massive river sustained a vast, inland sea centred on modern-day Botswana. The present article draws on our recently published paper in the *South African Journal of Geology:* 'The Zambezi River: an archive of tectonic events linked to Gondwana amalgamation and disruption, and subsequent evolution of the African Plate'.

I summarize how all the evidence reveals the origins and history of this ancient river, and conclude in emphasizing the world heritage status of the Luangwa and Zambezi valleys. Remarkably, science knows little about the absolute ages of the world's oldest rivers. One needs firm evidence to qualify that a river is truly ancient. As in the case of the Zambezi, certification demands an unbroken chain of evidence linking today's river with its earliest known ancestral land-forms back into the remote geological past. In the scholarly literature, the Mississippi has long stood alone: traceable back to a Proto-Mississippi established ~250 million years ago (Ma). Some of the other popular claims of ancient rivers are, in contrast, poorly resolved; notably, the Finke of central Australia is claimed to be the direct descendant of a 340 Ma old river. Yet, the contiguous record of a Finke river stops at 100 Ma, distinct from 340 Ma traces of a very different river in the Carboniferous. In between a gap in sediment deposition of 200 million divides the tenures, of two distinct rivers.

The Gondwanan Legacy of the Proto-Zambezi

Pre-dating the Mississippi's record, the Zambezi is at least 30 Ma older, because an unbroken chain of evidence places a minimum age of 280 Ma on its origins, when Gondwana's ice-sheets began to melt as the super-continent drifted northwards. Central Africa's rift valleys preserve the rock ledgers (historic record) that tell us the Proto-Zambezi existed long before Africa became a continent. Importantly, this geological record of the ancestral Proto-Zambezi is contiguous with the modern river. In particular, the evidence reveals that precursors of the modern Luangwa and Middle Zambezi already existed in the early Permian. This geological record in the Luangwa and Middle Zambezi valleys (the central African rifts) has survived despite the complete reversal of the Zambezi's flow caused by Gondwana's breakup, which forged the African continent. The contiguous rock record initially formed on Gondwana built up sediments several kilometres deep within the central African rift



Upper Map (A) of the Gondwana Super-continent to show the Proto-Zambezi river (thick blue line) and the massive Trans-Gondwana Super-Mountains, at the time when the Indian Ocean has began to form during the breakup of Gondwana (approximately 160 Ma). This west-flowing Proto-Zambezi drainage system maintained a vast inland Karoo sea. The original extent of the Karoo sediments was likely larger before the break up and erosion associated with formation of the daughter continents of Gondwana. Inset (B) details these centres of Karoo deposition (shallow lakes, seas and deltas) depicted in darker shading, as represented in surviving rock formations in southern and central Africa. The superimposed dashed line approximates the position of the modern, east-flowing Zambezi river

valleys. They comprise formations of the Karoo system, well known across the southern continents (Antarctica, Australia, India and South America). The very oldest Karoo rocks formed in glacial valleys, during the global Dwyka ice age, when massive glaciers covered much of the super-continent; this was long before initial formation of the African rifts consolidated the sediments deposited by the Proto-Zambezi drainage system. Initiation of the Proto-Zambezi at 280 Ma sets the minimum estimate on when its flow began in inherited glacial Dwyka valleys, but the very first drainage could be even older. The watersheds of this massive river tapped Gondwana's (if not the planet's) largest mountain range. Over 8000km in length, the Trans-Gondwanan Super-mountains far exceeded the stature and extent of the Himalayas. Long before the Dwyka and Proto-Zambezi times, these mountains had formed along metamorphic collision belts, when the continents collided to form Gondwana700-600 Ma. Today, the metamorphic belts isolated on Antarctica and tropical Africa (including northern Mozambique) are the vestigial roots of these Trans-Gondwana Super-mountains: the last survivors of millions of years of erosion.

Tectonics and Continental Evolution

The collective evidence for the Zambezi's origins testifies to how the processes of plate tectonics have formed and reshaped continents. This geological record reveals the innate sensitivity of large rivers to tectonism; and indeed, geologists can read the sedimentary record and physiography of an ancient river as an evolutionary ledger, which reveals how the passage of tectonic events impacted across its host continent. In the Zambezi's case, pulses, sources and fates of sediment flux tell us how this ancient river responded to repeated continental warping and cracking, over millions of years as a polar super-continent was transformed into a tropical continent straddling the equator.

The Zambezi's sediments document the two main episodes of tectonism that occurred in this epic odyssey of Gondwana and its daughter continent. Despite being separated by millions of years, two complementary libraries of sediments link these chapters of the Zambezi's evolution. We can read the oldest in the sedimentary rocks across the Luangwa, Gwembe, Cahora Bassa and Mana basins. The records of the second library are shelved offshore in the Zambezi Delta. The change in archiving site was caused by incremental expansion of the Lower Zambezi's basin through the Mesozoic, which rejuvenated erosion and deposited sediments offshore of Africa. Beginning with Cahora Bassa, this erosion episode advanced inland, and continued to re-work the sediments preserved in the Gwembe and Luangwa valleys. Crucially, the rifts' records were not scoured out entirely, because these sedimentary piles have only been partially incised. The surviving exposures in the rifts hold a rich history. So the complementary outcomes of sediment flux and storage have proved fortuitous for geologists - to map and correlate the pages of the stratigraphic record across these rifts.

On the platform of the Dwyka glacial sediments, the Proto-Zambezi began to build its first library 250 million years ago, in Triassic times, when Gondwana began to break up. Its acquisitions of sediments persisted until near the final break up of the super-continent. This isolated Africa entirely at 120 Ma. During this process the Indian Ocean as the Zambezi's offshore delta grew along Africa's east coast.

Even more recently, partnered with neighbouring African rivers, the Zambezi continues to shape yet a third library; its sedimentary records are accumulating in Africa's inland rifts and along its east coast. Sediments began to build this third, more scattered, library system about 30 Ma, in response to widespread tectonics of the East African Rift System (EARS), which includes the Gwembe and Luangwa, and neighbouring rift valleys. Today, recurring subtle rifting and seismic activity reveals the EARS is expanding south through Mozambique, and southwest across Zambia into Botswana. The greatest change in over 280 million years of the Zambezi's evolution entailed the complete reversal of its flow (albeit the Luangwa has always flowed southwest, Fig 4). This reversal in flow, from west to east, of the Middle and Lower Zambezi began as Antarctica and Australia broke away from Africa. The process of break up was protracted, as over millions of years, river by river, flow in the Proto-Zambezi's catchment was redirected into the Indian Ocean, to reduce the significance of the Proto-Zambezi's inland terminus (in central Botswana). In converse, the Zambezi's catchments expanded around its terminus on the Indian Ocean, because aggressive erosion pirated the Proto-Zambezi's tributaries. Adjustment to sea level has driven this expansion across central Africa's interior, ever since the Zambezi's terminus formed in the Indian Ocean. Notwithstanding the many piecemeal changes, through its entirety of history the primary skeleton of the Proto-Zambezi has framed the metamorphosis of drainage system.

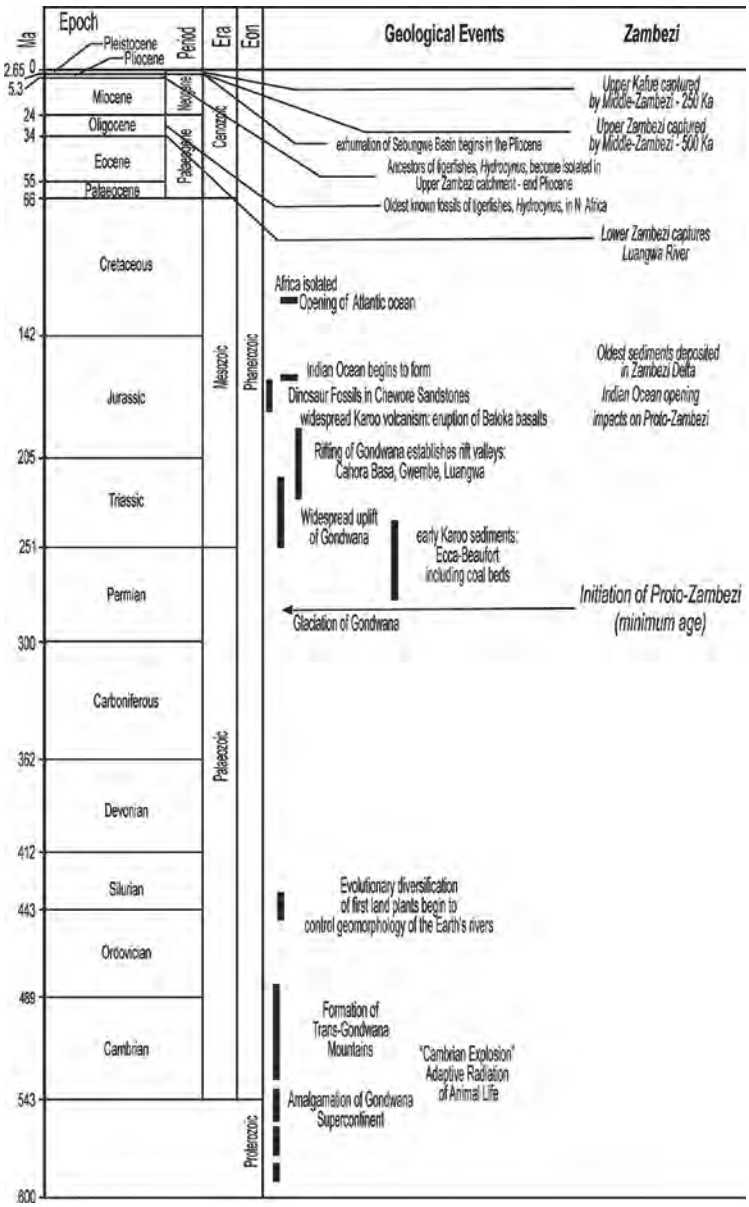
The Zambezi river lies within the focus of more recent uplift and rifting, which continues to impact on Africa's landscapes long after the continent formed. The geomorphological evidence for these recent events is complex. It complements the older records preserved in the Zambezi's rifts and delta. Our understanding of this recent history has improved greatly over the past two decades (see Further Reading) and its details will fill a separate essay. We can read the main signatures of these changes in fingerprints of the Proto-Zambezi heritage preserved across Central Africa. Revealing evidence is preserved outside the modern Zambezi basin. For example, the Lugenda, Rovuma, and Upper Kilombero rivers flow east today, but are vestiges of Proto-Zambezi headwaters that flowed southwest.

Equally, primary Zambezi tributaries preserve evidence of upheavals in their origins. The Luangwa's eastward outflow along the Lower Zambezi testifies to its redirection at about 35 Ma. No less significant events entailed the much more recent piracies of the Upper Zambezi and Kafue; they were both formerly land-bound rivers. This sequence of river piracies is not complete, because erosion by the Upper Zambezi, propagating upstream through the Chobe, will probably capture the Okavango as its next headwater; and the Selinda Spillway linking the Okavango and Chobe is the most likely precursor of this emerging link. These geologically recent captures of the Chobe, Kafue and Upper Zambezi testify to the relative youth of the river's topology. The Great Equatorial Divide on Africa's high plateaux comprises the Zambezi's modern watershed, and its present position testifies to repeated re-shuffles of links between long lived rivers. To summarize, we now estimate the modern Zambezi basin to be barely 250 thousand years old.

Zambezian Rifts: Sediment Archives in Gondwana's Rift Valleys

It is interesting to scrutinize the keystone roles of the rift valleys (called graben in geology) bequeathed by the Gondwana super-continent; not least, because their sediments archive the primary evidence of the Zambezi's longevity. Moreover, the outstanding fossil beds and extant ecology of this remarkable natural heritage greatly expand the global significance of a unique wilderness in the heart of central Africa. In this section, I expand on the keystone roles of these rift valleys as evolutionary libraries, which underpin our insights.

The layer-cake of Karoo sediments, undisturbed since Gondwana times, did not escape the rejuvenated erosion that formed the modern Zambezi basin, when erosion incised and opened out the rift valleys. The Roman's god of gateways – Janus – serves as the apt metaphor to illustrate how rifts controlled sediment flux and storage. The switch from deposition to erosion underwrites the fortuitous contiguity of



Geological timeline showing the principal events in the evolution of the Zambezi river on Gondwana and the Africa, in relation to major geological conditions and episodes

Zambezi's rock record – first preserved in the old library across the rifts, and then its more recent archives shifted offshore to form the Zambezi Delta. Stored for millions of years after their burial, erosion re-shelved the old Gondwana sediments offshore in submarine archives as marine sediments. This erosion of central Africa removed tonnes of rock, much of it Karoo sediments many millions of years after they first formed inland. By replacing the role of the Proto-Zambezi as primary record-keeper, the eroding Zambezi took over direct recording of its own evolution; preserved as great lenses of sediment in submarine vaults, the Zambezi delta documents sources and times of transport from eroding catchment to marine terminus. Kilometres of cores have been drilled across the Mozambique Channel seeking offshore oil. These drill cores fix the start of the unbroken marine record of the Zambezi delta in the Jurassic at 150 Ma. In summary, long after the Proto-Zambezi had stacked its sedimentary piles into Gondwana graben, the rejuvenated Zambezi disinterred the same sediments for their final burial in Indian Ocean. These events that have shaped and reshaped the evolving Zambezi hold exemplary lessons. The venerable legacy of the old river is one. It qualifies as a multi-stage landform; remarkably, on an evolving landmass, the life span of the Zambezi spans the fates of two different continents. This legacy adds new depth to contemplate when basking in your next Zambezi sunset! Here, our Janusian metaphor highlights how intra-continental rift valleys have provided the refugia, which enabled a big river to survive millions of years of geological and climatic upheavals: even the splitting up of its host continent.

(a) and (b) Sauropod footprints provide tangible evidence of the giant vertebrates that once dominated Zambezian ecosystems at about 170 Ma. (c) trackway of a theropod dinosaur in a dry riverbed in the Chewore Safari Area. Note the elephant dung testifying to how African elephants tread on footprints preserved in the damp Proto-Zambezi sands of Gondwanan times. (d) Fossil bones of a Massospondylus *dinosaur.*

We see the second lesson in the no less remarkable contrast between the ages of the Zambezi's tributaries, compared against their reworked links, such that ancient rivers forming the modern basin have been shaped by very young links. The Luangwa exemplifies this contrast of the oldest river still at work on its second host continent. Its recent, east-flowing link with the Lower Zambezi formed hundreds of millions years after the Luangwa first began to flow southwest. This contrast in age exemplifies how the flows in river after river have been reshaped between ancient river basins. Contingent on its records, an ancient river can reveal hidden aspects of a continent's history; the Zambezi's record suggests we can decipher similar records in other big rivers.

Global Context: Signatures of Antiquity

The perennial Zambezi has directed and contained the fates of human activities for millennia. Repeatedly, the river has undone the best laid plans; explorers' travelogues testify how the Zambezi humbled and thwarted the ambitions of the most tenacious hunters, missionaries and traders. The same old challenges remain. The river's geostrategic dominance is undiminished. Persisting tectonic activity complicates any plans for natural resource exploitation – especially impoundments. Look no further than the complex structural geology of the rifts, and especially recurring impacts of tectonics on Kariba!

I close this narrative by singling out the most tangible evidence, preserved along the Zambezi. It raises appreciation of the less obvious aspects of the Zambezi river's origins, and broadens our insights into the wilderness values of the region. The highlighting of these ancient attributes of the wilderness are all the more poignant; they deserve to become widely respected – not only in words but all for the better through practical conservation. The bearing on conservation lies in how the ecological facets of this venerable river serve up the most fascinating evidence of its antiquity. We can read their lessons in the tangible links between ecosystems and Zambezian landscapes. A geological perspective is essential to appreciate how the biodiversity and ecology of today's Zambezi extends back to its deep Gondwanan origins.

We see the best examples away from the popular destinations, where one can still enjoy the privilege of exploring Zambezian wilderness, and this is where no lack of surprises and challenges persist. Long before the first civilizations ever existed, our hominid ancestors lived here amongst the wildlife, the diseases, and the formidable terrain. I single out several bodies of charismatic evidence to illustrate this ecological connectivity between Zambezian biodiversity, past and present:

• Exposures of sedimentary rocks preserve especially tangible aspects of the deep antiquity of the valley's biodiversity. The oldest fossils comprise the fossil fragments of Glossopteris – that dominated the charismatic primitive flora of Gondwana, and its preservation in the oldest Karoo rocks gives us tangible evidence of the former links between the southern continents. You can see even more impressive evidence at first hand in the Luangwa and Zambezi valleys. These comprise Mesozoic fossil beds, which preserve abundant fossil

The journey north from Makuti reveals dramatic evidence of the ancient geological history in the road cuttings. The folding and faulting of these rock formations along the Zambezi Escarpment testify to impacts of several episodes of tectonic activity. The earliest occurred long before the formation of the Gondwana super-continent

evidence of extinct vertebrates. These fossils formed in the river's evolving sediments include charismatic species of dinosaurs that lived and died in the rifts.

• Notable species of the dinosaur fauna included: a larger predatory allosaur, *Vulconadon karibaensis;* a giant sauropod, *Brachiosaurus* sp.; and the diminutive coelosaurian, *Syntarsus rhodesiensis*, the species superbly documented in the world famous display in Bulawayo's Natural History Museum.

• Dinosaur trackways preserved in sandstones in the southern Chewore Hills of northern Zimbabwe open especially impressive insights into this extinct biodiversity. These well preserved fossil trackways reveal where giant vertebrates trampled Jurassic sands in the drainage of the Proto-Zambezi.

• This dinosaur legacy gives us a handle to grasp the immense spread of geological time, opening a window on the Jurassic era when dinosaurs stalked the Zambezi valley. Yet, the Proto-Zambezi was already at least 150 million years old, so already well into its middle age. And many more millions of years passed before the first mammalian mega-herbivores drank from the Zambezi.

• The earliest crocodiles appear in Africa's fossil record in the Cretaceous, albeit elsewhere on the continent. Fishes are known to have populated the Zambezi since the Jurassic, at least. The evidence includes complete Lepidote fossils found near the dinosaurs in Chewore. These fishes swam in Zambezi waters over a hundred million years before the remarkable African fish fauna existed. The first known ancestor of the tigerfishes, genus *Hydrocynus*, is known from Oligocene fossil beds in North Africa, dated at 35-21 Ma. The evidence in DNA sequences reveals the Zambezi tigerfish, *H. vittatus*, evolved within the confines of the Upper Zambezi river, where it became isolated from neighbouring populations in central Africa within the past 2-3 Ma. And *H. vittatus* only finally colonized the Middle Zambezi below the Batoka gorges within the past 200 000 years.

These selected examples reveal how ecological associations have sustained Zambezian biodiversity since Karoo times, ever since the Proto-Zambezi began to work its loads of silt and shifting sands. Then, as today, the local attributes, and not least the very existence, of every Zambezian ecosystem has depended on mineral nutrients in the soils, either in freshly deposited sediments or weathered from underlying rocks. This maintenance of the physical substrates and nutrients, on which the biodiversity has evolved, reveals yet another Janusian role of the Zambezian rifts. The inherited fluvial sediments enduring in these sediment silos were bequeathed to Africa from its parent Gondwana. Mineral nutrients have flowed through a myriad food-webs in Zambezian ecosystems that have assembled on successive valley floras over hundreds of millions of years. These ecosystems included the ancient and then modern fish faunas, and equally those dominated by dinosaurs, long before mammalian pachyderms existed. We can see the most palpable evidence of this continuity where elephants on their paths tread and trample dinosaur trackways! It was only in the last few million years that we see evidence of occupation of the Zambezi basin by our hominid ancestors, and widespread archaeological evidence testifies to hominid occupation of the Luangwa and Zambezi valleys since the Early Stone Age.

This status as Earth's oldest, big river – yet known – underwrites the conservation status of the Luangwa-Zambezi wilderness. The geological continuity preserved across these landscapes reveals how the ecosystems of the Zambezi have endured in an unbroken chain, ever since the first ecosystems of Dwyka times formed along glacial streams. The criterion of **Ancient Evolutionary Heritage** positions the Zambezi as a unique outlier among Earth's most spectacular landscapes, including the Grand Canyon. One is challenged to name World Heritage Sites that match these iconic values, in preserving comparable geological and paleoecological records.

The Luangwa river has flowed to the southwest for at least 280 million years as a north bank tributary of both the Proto-Zambezi and the modern Zambezi rivers. Here its channel has incised recent deposits of alluvium, reflecting how this big river has worked its sediment loads over the eons

Acknowledgements

Like many readers of this unique magazine, Zambezi experiences enrich my earliest memories, and I have been fortunate this privilege has endured in repeated expeditions all along its landscapes from source to delta. I thank the many friends and scientific colleagues, past and present, who have aided, abetted and participated in remarkable experiences along the Zambezi and elsewhere. Last, and not least, Jan Teede and Helen Teede are thanked for kind use of their photographs of a unique global heritage.

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