THE ZAMBEZI RIVER: AN ARCHIVE OF TECTONIC EVENTS LINKED TO THE AMALGAMATION AND DISRUPTION OF GONDWANA AND SUBSEQUENT EVOLUTION OF THE AFRICAN PLATE

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ABSTRACT

Africa's modern Zambezi is proposed as an example of a major extant river system, which archives the tectonic events that assembled and then fragmented a supercontinent. The Zambezi and an earlier Karoo river system, (here designated the Proto-Zambezi River system), have a recorded geological history spanning approximately 280 million years. Its original headwaters were formed when the End-Neoproterozoic to Ordovician amalgamation of the Gondwana Supercontinent created a central Himalayan-scale mountain belt, now called the Trans-Gondwana Mountain Range (at the core of the East Africa-Antarctica-Orogenic Belt). Eroded remnants of these mountains were the source of west-directed Dwyka glacial sediments and Ecca and Upper Karoo, Permo-Triassic, rift-controlled lakes and rivers across West Gondwana. The reversed drainage of the Zambezi River started to flow eastwards through the same rift valleys in the Middle Jurassic (at about 165 Ma), as Africa started to separate from the eastern part of West Gondwana, with the resultant development of an eastern seaboard. This second stage in the evolution of the Zambezi River mirrored sequential openings of the Indian and Atlantic Oceans, in the post-Gondwana interplay between epeirogeny and rifting. Protracted longevity of the Zambezi River and its ancient precursor shows that major drainage systems can survive plate break-up, albeit with changed flow directions and continuously evolving catchments.

Introduction

The Zambezi River is the 4th longest of Africa's present-day great river systems, originating in central southern Africa, and flowing southwards and eastwards for over 2500 km into a flood plain in central Mozambique (Figure 1). It is proposed that the lower and middle parts (within the Cabora Bassa Rift-basin and the Mana Pools and Mid-Zambezi Basins) of the modern Zambezi River follow the same rift valleys as a major Permo-Triassic (Karoo) lake and river system, which originally flowed westwards across the interior of the (Western) Gondwana Supercontinent (Figure 2). The headwaters of this Gondwana river system drained eroded remnants of mountains formed by Neoproterozoic-Cambrian orogenesis associated with the amalgamation of West and East Gondwana (Tiercelin and Lezzar, 2002; Blenkinsop and Moore, 2012; Figure 2). Here we reconstruct the origins and dynamics of this ancient drainage system, designated the Proto-Zambezi River system, and further summarize its evolution over the past ~290 million years into the modern Zambezi River.

Previous work on the Karoo strata preserved within, from east to west, the Cabora Bassa Rift-basin, the Mana Pools and Mid-Zambezi basins show rift-bounded Dwyka Group glacial sediments and overlying Ecca Group low-energy, coal-bearing, fluvio-lacustrine sediments. These are overlain by Upper Karoo high-energy fluvial sediments (of the Cãdzi Formation in Mozambique and the Escarpment Grits and Angwa Sandstone Formation in Zimbabwe; Table 1) variously classified into the Beaufort or Stormberg Groups (e.g. Oesterlen and Millsteed, 1994; Johnson et al., 1996; Ait-Kaci Ahmed, 2003; Lächelt, 2004; Hatton and Fardell, 2011). Our work confirms that the high-energy fluviatile sediments were laid down by a west-directed river system. Isolated remnants of aeolian/fluviatile sandstones and bimodal (acid/basic) volcanic rocks locally overlie the high-energy fluviatile strata (Lächelt, 2004; Catuneanu et al., 2005; GTK Consortium, 2006).

Following break-up of West Gondwana, the first order channel of the Zambezi River followed the same rift valleys as the Proto-Zambezi River system, albeit

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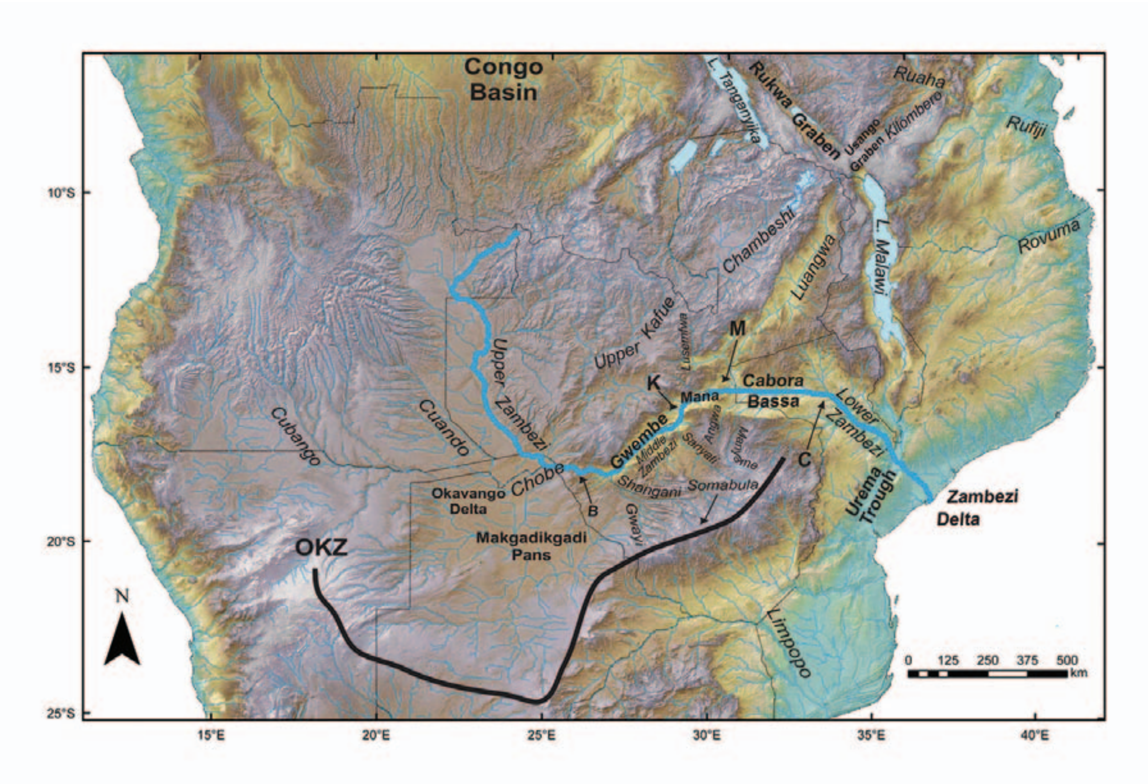

Figure 1. *The extant drainage network of south-central Africa illustrating major rivers and landforms mentioned in the text, including the Okavango-Kalahari-Zimbabwe (OKZ) epeirogenic axis (thick black line) and the Batoka (B), Cabora Bassa (C), Kariba (K) and Mupata (M) gorges. See main text for details of Karoo facies mapped in the Cabora Bassa sub-basins. The three main sections comprising the extant Zambezi River (thick blue line), have each exhumed extensive valleys upstream of these respective gorges, with the Upper Zambezi and associated Kalahari Plateau tributaries the most recent addition to the drainage net (Digital Elevation Model modified from NASA Shuttle Radar Topography Mission -3).*

Table 1. Lithostratigraphy of the Cabora Bassa Rift-basin and the Mid-Zambezi Basin. Data from Nyambe and Utting (1997), Cairncross (2001), Lächelt (2004), Catuneanu et al. (2005), Vasconcelos (2009), Hatton and Fardell (2011) and Rubidge et al. (2013).

Karoo Group	**Age for Cabora Bassa sequences**	**Mozambique-Cabora Bassa**	**Eastern Zimbabwe-Cabora Bassa**	**Mid-Zambezi Basin (Zimbabwe)**	**Mid-Zambezi Basin (Southern Zambia**
Stormberg (about 230 to 173 Ma)	Late Triassic to Early Jurassic	Bimodal volcanics and red sandstones	Forest Sandstone	Forest Sandstone	
	Late Triassic (about 230 to 209 Ma)	Bimodal volcanics and red sandstones	Pebbly Arkose	Pebbly Arkose; Fine Red Marly Sandstone; Ripple Marked Flagstone	Red Sandstone Interbedded sandstone and mudstone
Beaufort (Base 264 Ma)	Late Permian to Early Triassic (about 255 to 237 Ma)	Cădzi	Angwa Sandstone	Escarpment Grit	Escarpment Grit
Ecca-Beaufort	Late Permian (about 272 to 255 Ma)	Matinde	Mkanga	Madumabisa Mudstones	Madumabisa Mudstones
Ecca (280 to 265 Ma)	Early Permian (about 280 to 272 Ma)	Moatize	Mkanga	Wankie	Gwembe Coal
Dwyka (≥302 to 280 Ma)	Late Carboniferous to Early Permian	Vüzi	Kondo Pools	Dwyka Glacial Beds	Siankondobo Sandstone

with a diametrically reversed flow direction across south-eastern Africa. Reconstructions of the African Plate since the break-up of West Gondwana during Middle Jurassic times, at about 165 Ma (Table 2), show that the east-flowing Zambezi River is as old as the African continent (Reeves 2009, 2013). Indeed, Salman and Abdula (1995) record Upper Jurassic sediments within the Zambezi delta developed offshore of central Mozambique.

The river's subsequent history is dominated by river captures, notably piracies of major tributaries that progressively increased the catchment of the Lower Zambezi (Moore and Cotterill, 2010; Moore and Larkin, 2001; Moore et al., 2007; 2009a; b; 2012). These changes to the river system were in turn linked to crustal uplift during, and following, disruption of the Gondwana Supercontinent. Nevertheless, since the opening of the Atlantic Ocean (at about 125 Ma) the river's first order channel has apparently followed a consistent course into the Indian Ocean (Moore and Larkin 2001).

Protracted inheritance of drainage systems within and between intracontinental grabens (together with the

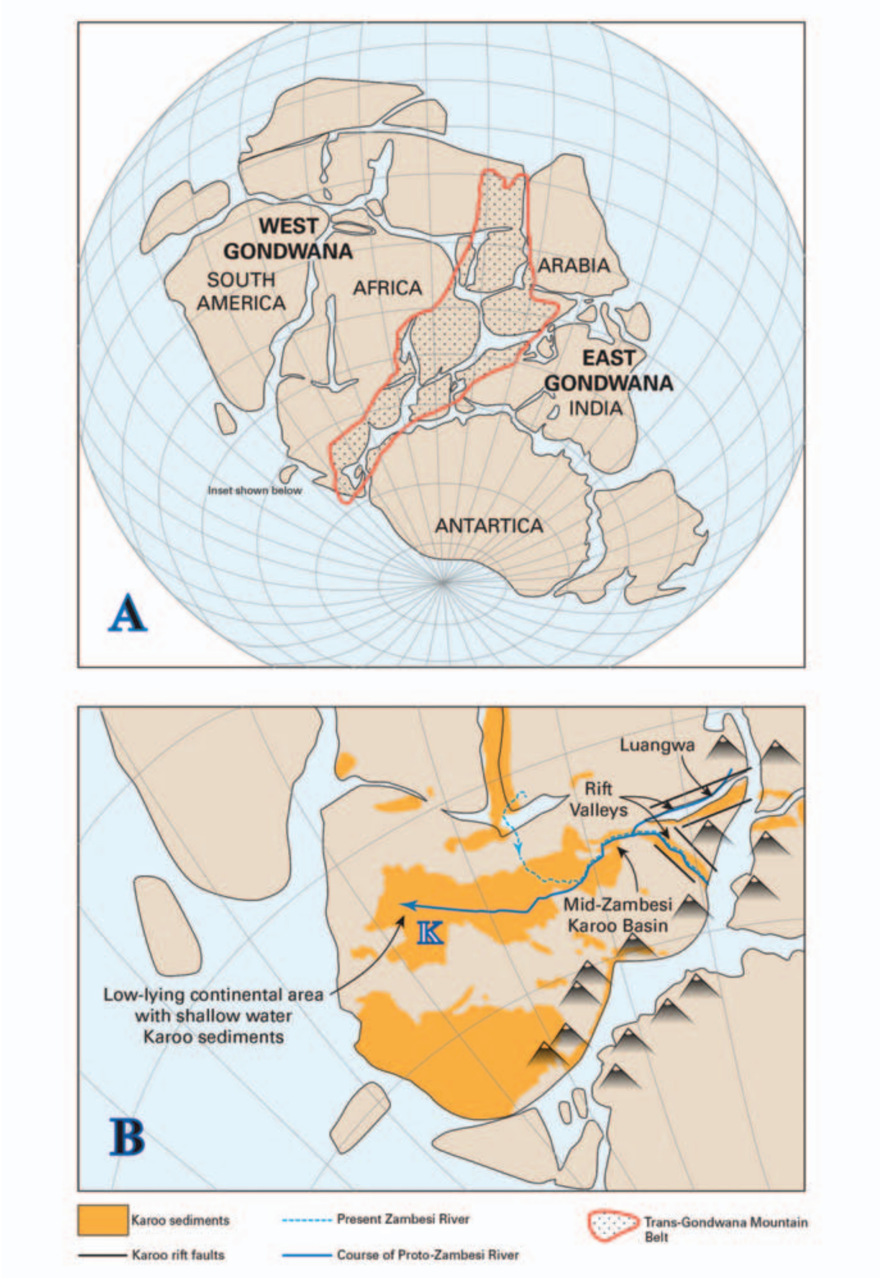

Figure 2. *The central location of the Trans-Gondwana Mountain Belt within the Gondwana Supercontinent (based on the reconstruction by Reeves, 2009). (**B**) Early Permian palaeogeography of the Proto-Zambezi River across Western Gondwana (from Smith, 1984; Guillocheau et al., 2013a); the blue lines trace the approximate course of the river into the Kalahari Basin (K).*

Table 2. A summary of the major Phanerozoic events that modified the central and south-eastern portions of the African Plate prior to about 93 Ma, and relevant to the evolution of the Proto-Zambezi and Zambezi River systems. See main text for detailed references.

Age (Ma)	Event
93	Opening of Mascarene Basin establishes the eastern Africa shoreline as a passive margin.
130 to 90	Isostatic uplift and erosion of eastern and central Africa.
135	Complete separation of East Africa from Madagascar.
145 to100	High energy proximal sedimentation along Africa's developing eastern coastline.
165	South facing gulf started to develop between East Africa and Madagascar (start of West Gondwana break-up). **Lower Zambezi River flowing eastwards**; Reeves (2013) reconstruction.
201 to 165	Siliciclastic sedimentation in half grabens adjacent to (and along) the line of separation of East Africa from Madagascar, and at an angle to the earlier Karoo rift-basins.
184 to 173	Karoo magmatism – sub-continental flood basalts, bimodal volcanic centres in rift-basins and regional dyke swarm.
258 to 210	Erosion related to uplift with drier climate (uppermost Karoo sedimentation).
280 to 237	Ecca-Beaufort Groups sedimentation: fluvio-lacustrine 'coal measures' overlain by **west-directed high-energy, fluviatile sedimentation in the Proto-Zambezi River through the Mid-Zambezi Basin and Cabora Bassa Rift-basin**.
≥302 to 280	Dwyka glaciation of Gondwana with west-directed ice movement across West Gondwana off the Trans-Gondwana Mountain Belt.
420 to 302	Unknown amount of sedimentation in central-southern Africa; most removed by the Dwyka glacial event.
480 to 420	End of magmatism within the Pan African orogenic belt system with relatively slow crustal cooling until 420 Ma.

latters' infilling and then reactivated rifting) holds deeper significance, because they qualify as persistent multi-stage landforms (*sensu* Twidale 2000; 2005). Persistence of such long-lived landforms is explained, and best understood, when they are classified as individuals; the latter term is used here in the explicit ontological sense – analogous to the origins and fates of species and phyla in biological evolution. In fact, the aptly named Individuality Thesis (Ghiselin 1997; 2005a) encompasses geologists' reconstructions of the unique histories of evolving lithospheric individuals; this approach is exemplified in deciphering the origins and fates of plates and their parts. The most remarkable examples of such parts are long-lived terranes (cf. Le Grand 2002; Echeverry et al., 2012). Expanding the envelope to account for the reconstructed histories of long-lived rivers, and other ancient landforms, places the dynamics of evolving geomorphological entities firmly into the causal framework of plate tectonic theory (Le Grand, 2002; Ghiselin 1997; 2005a; b).

Our collated evidence for this lengthy history (over at least 280 Ma) of the Zambezi River and its precursor Permo-Jurassic River confers broader context to interpret events in the tectonic evolution of Gondwana prior to, and following on, the individuation of the African plate. One, their record of tectonic events tracks the disruption of Gondwana, and the ensuing evolution of the African Plate. Two, this tectonic archive, in turn, offers potentially valuable insights into the underlying processes responsible for the geomorphic evolution of south-central Africa. Three, the consequence is that rift-controlled valleys that survive plate separation can preserve key evidence to reconstruct extinct super-continents (Delvaux, 2001; Potter and Hamblin, 2006; Roberts et al., 2012a) Four, resolving the evolution of major, long-lived rivers is also critical in evaluating the potential for sediment-hosted mineral deposits in their deltas (Garzanti et al., 2014). For the Zambezi this includes the hydrocarbon potential of its delta off central Mozambique, and for the more northerly sedimentary basins off the coast of East Africa this could include coal and coal-bed methane in possible basal Karoo lacustrine sequences.

The Karoo river system in West Gondwana

The Pre-Karoo regional geological setting

The Gondwana Supercontinent formed by Neoproterozoic orogenesis in intersecting linear orogens, including the north to south trending Pan-African, East Africa-Antarctica Orogen (EAAO) that effectively separated West and East Gondwana (Pinna et al., 1993; Meert, 2003; Jacob and Thomas, 2004; Kröner and Stern, 2004). Major post-collision granitic magmatism concomitant with regional uplift and crustal cooling in the EAAO ended at about 480 Ma (Bingen et al., 2009). This resulted in the formation of a major linear mountain belt forming the core of the EAAO, here referred to as the Trans-Gondwana Mountain Belt. It encompassed what is now the east coast of Africa (Bingen et al., 2009; Figure 2). Pressure-Temperature signatures of metamorphism determined from rocks that formed the orogenic core, in northern and central Mozambique, reveal a mountain belt of Himalayan proportions (Engvik et al., 2007; Grantham et al., 2008). Campbell and Squire (2010) present atmospheric oxygen values as supporting evidence for an 8000 km long 'Gondwanan Supermountain Belt'.

Fission track profiles in Mozambique (Daszinnies et al., 2009; Emmel et al., 2011) indicate gradual erosion of the mountain belt throughout the Palaeozoic Era. However, there is little preserved evidence in central-southern and southeastern Africa of any pre-Carboniferous detrital sediments derived from the weathering. An exception is provided by the Sinakumbe Group from the Zambezi Valley in southern Zambia, which underlies the oldest (Dwyka Group) Karoo-strata; and is equated with the Ordovician-Devonian Cape

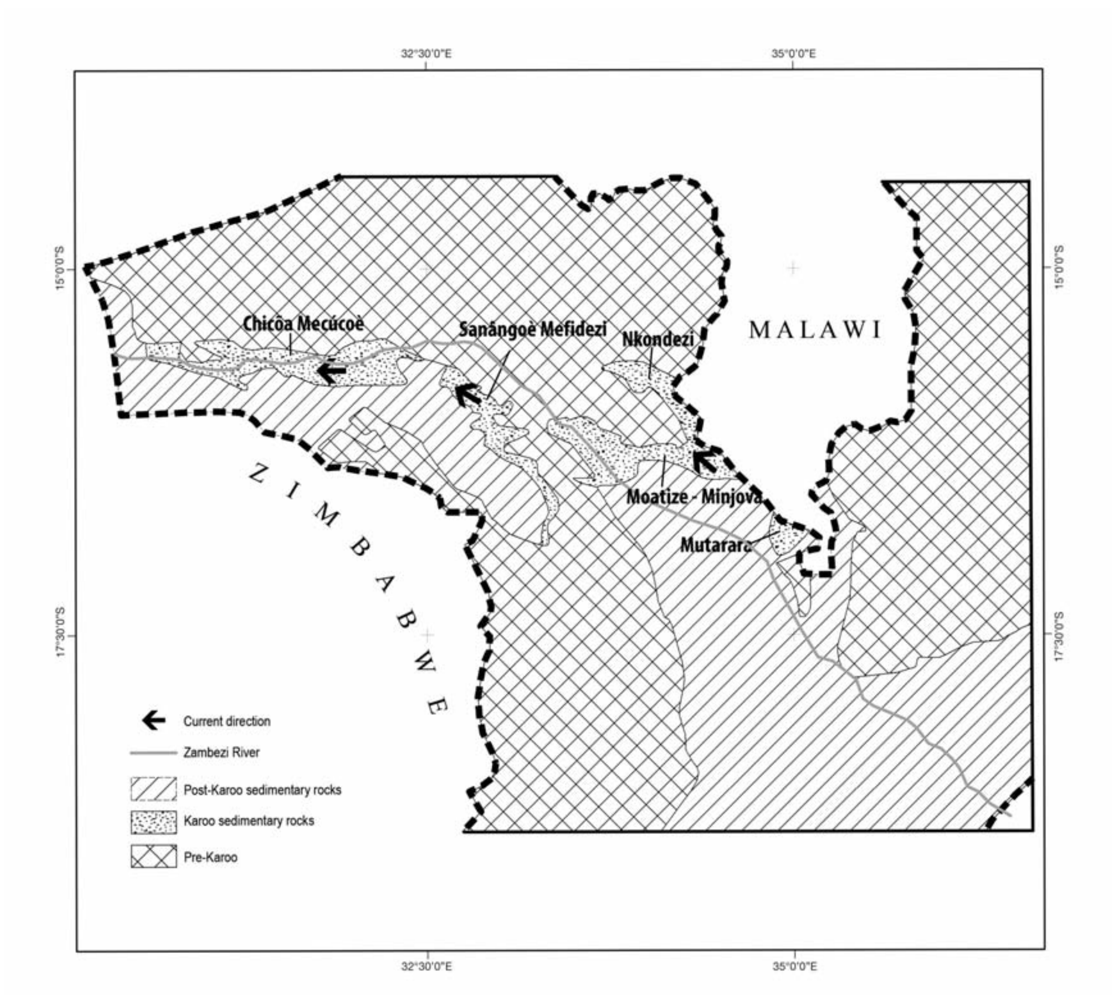

Figure 3. *The locations of the three major Karoo sub-basins in northwest Mozambique showing the dominant current directions based on cross-bedding readings from Cădzi Formation sandstones.*

Supergroup in South Africa by Nyambe and Utting (1997). The general absence of the Early Palaeozoic rock record can be explained by the long-lived Dwyka glaciation (≥303 to 280 Ma; see below), which must have effectively stripped the Gondwana land surface of any Lower Palaeozoic sedimentary cover to expose the underlying Precambrian basement.

Karoo Sedimentation across West Gondwana

The Karoo Supergroup of southern and eastern Africa comprises the Main Karoo Basin of South Africa (a foreland basin to the Cape Fold Belt) and other smaller basins and elongate rift-basins (Kreuser, 1995; Johnson et al., 1996; 2006; Catuneanu et al., 2005) that unconformably overlie mostly Precambrian rocks that formed the crystalline basement of West Gondwana. The subsidiary Karoo basins and rift-basins include the interconnected (from west to east) Kalahari Basin, and the Mid-Zambezi and Mana Pools basins, and the Cabora Bassa Rift-basin along what is now the Zambezi River Valley in north-western Mozambique and eastern Zimbabwe (Figure 2). The lithostratigraphy at Group level for the Main Karoo Basin has been applied to other Karoo basins because the same sequence of major sedimentary palaeo-environments is recognised everywhere (Table 1).

Fieldwork between 2011 and 2013, as part of a mineral exploration programme, was undertaken along the Cabora Bassa Rift-basin between longitudes 30°45'E and 34°30'E in north-western Mozambique by the lead author (Key 2011a; b; 2013). Nine sub-basins are recognised in the Cabora Bassa Rift-basin of the Zambezi River valley of Mozambique (Lächelt, 2004). From west to east these are; Mecücuè; Mucanha-Vüzi; Chicoa; Mafidézi; Sanângoe; Moatize-Minjova; Muaradzi-Mecondezi; Estima-Changara and Baicho Chire (Figure 3). Subsequently, Vasconcelos (2009) combined these sub-basins into three larger basins, namely, from west to east; the Chicôa-Mecúcoè, Sanângoè-Mefidezi and Moatize-Minjova sub-basins (Figure 3) with the smaller Nkondezi and Mutarara Sub-basins to the northwest and southeast respectively. Detailed mapping was undertaken within parts of the three larger sub-basins. The Karoo strata are assigned to the same formations in all the sub-basins (Table 1), following Lächelt (2004).

The Cabora Bassa sub-basins are all bounded, on one side at least, by major rift faults that locally reactivate major structures in the underlying Precambrian crystalline basement. They include the Sangoegoe Shear Zone in Mozambique; east to west trending faults on the north side of the Chicõa-Mecúcoè Sub-Basin and northwest to southeast trending faults forming the north-west side of the Moatize-Minjova Sub-basin (Koistenen et al., 2005; Mäkitie et al., 2005; Manninen et al., 2005; Marques et al., 2005; Tahòn et al., 2005; GTK Consortium, 2006; Key 2011a; b; 2013). The Cabora Bassa Rift-basin closely parallels and partly obscures the Zambezi Metamorphic Belt, which rims the northern margin of the Zambezi Craton. This reflects the strong preference for continental rifting to exploit mobile terrains surrounding stable crustal blocks (Broderick, 1990). Geophysical evidence indicates up to 4000 m of sediments within the Cabora Bassa Rift-basin, with the basin axis located to the north of the rift scarp which forms the southern margin of the basin (Broderick, 1990). Lächelt (2004) records a total thickness of up to 5000 m for Karoo sedimentary strata including 130 m for Stormberg Group (Caramacafue) sandstones and up to 1500 m of Stormberg volcanics, mostly found in the south-eastern part of the rift-basin. Our mapping indicates up to about 6000 m of sedimentary strata and only about 100 m of volcanic rocks away from the main southeastern volcanic centre. (our field data).

A feature of the Cabora Bassa Rift-basin's geology is that faulting remained active throughout Karoo sedimentation (e.g. Broderick, 1990; Banks et al., 1995; Yemane and Kelts, 1990; Tiercelin and Lezzar, 2002; Cairncross, 2001; Ait-Kaci Ahmed, 2003; Catuneanu et al., 2005). Hatton and Fardell (2011) noted that unlike the majority of Karoo coal formations in South Africa that were deposited in fairly stable tectonic basins, Mozambique coals (in the Moatize Formation) were deposited in tectonically active graben-like basins. Our mapping confirms that movement along the bounding faults accompanied Karoo sedimentation. For example, in the Chicõa-Mecúcoè Sub-basin there is an angular unconformity between the Matinde Formation and overlying Cãdzi Formation (Key, 2011a). Post-Karoo vertical movement on the bounding faults also tilted Karoo strata in the Cabora Bassa Rift-basin.

Dwyka Group (Vüzi Formation) and conformably overlying lower Ecca Group (Moatize Formation) strata are confined to the centres of the sub-basins with overlying upper Ecca Group (Matinde Formation), and Upper Karoo (Cãdzi Formation) strata extending from the central parts to the scarp slopes of the sub-basins where they rest unconformably on Precambrian rocks (Catuneanu et al., 2005; Key, 2011b). Previously, Johnson et al. (1996) observed that the Lower Karoo sediments in the Zambezi Valley were laid down within a rift-basin so that the present distribution of the Karoo reflects the original distribution and is not due to erosion removing Karoo strata deposited outside of the rift-basin.

Dwyka glacial event

The Dwyka glaciation is constrained from about 302 Ma to about 280 Ma (Westphalian to Artinskian) by palynological data, as well as radiometric ages from ash layers (Key et al., 1995; Visser, 1996; Wopfner and Diekmann, 1996; Bangert et al., 1999; Stollhofen et al., 2000; Catuneanu et al., 2005). However, Streel and Theron (1999) and Norman and Whitfield (2006) have suggested an older (Carboniferous) starting age for this glaciation, which therefore lasted for at least 22 million years. West and south-west directed ice movement off eastern highlands (i.e. calving off the eroding Trans-Gondwana Mountain Belt) is indicated across south-central Africa (Stratten 1968; Bond 1970; Truswell, 1977; Smith, 1984; Banks et al., 1995; Ait-Kaci Ahmed, 2003). As noted above, Dwyka Group (Vüzi Formation) strata were confined to central parts of the Cabora Bassa Rift-basin to imply that Dwyka glaciers either followed an existing valley or scoured out a new, probably structurally controlled, valley. The Vüzi Formation comprises a thin (260 m thick) fining upwards sequence of sediments inferred to have been deposited in a fresh-water glacio-lacustrine setting (e.g. Oesterlen and Millsteed (1994) or as fluvio-glacial deposits (Carvalho, 1960; Santos, 1974; Afonso, 1978).

Ecca low-energy fluviatile/lacustrine event

Conformably overlying the Vüzi Formation strata are Ecca Group (Moatize and Matinde Formation) coal measures that are interpreted as lacustrine and low-energy, fluviatile sediments with a combined thickness of up to about 3600 m (e.g. Afonso et al., 1998; Cairncross 2001; GTK, 2006). Huge lakes are identified within the Mid Zambezi and Mana Pools basins and western part of the Cabora Bassa Rift-basin during this time (e.g. Yemane and Kelts, 1990; Tiercelin and Lezzar, 2002). Yemane (1993) shows a huge Upper Permian lake system extending across southern Africa with a northeast to southwest trending lake extending from present-day Tanzania into South Africa connected to the lake defined through the Mid Zambezi-Mana Pools-Cabora Bassa Rift-basin.

Palaeo-current measurements taken from sandstone interbeds in coal-bearing sequences of the Moatize and Matinde Formations (our field data) do not show a dominant river flow direction. However, further west, Ait-Kaci Ahmed (2003) records west-directed currents in Ecca sequences in the Mid-Zambezi Basin. Regional studies show that southwesterly flowing rivers drained during Early Permian times into what is now central southern Africa (towards the western coastline of West Gondwana); where elevations were at, or near sea level with lacustrine and marine sediments recognised in the extreme west (e.g. Smith, 1984; Johnson et al., 1996; de Wit, 1999; Bangert et al., 1999; Stollhofen et al., 2000; Catuneanu et al., 2005; Guillocheau et al., 2013a; b;

Torsvik and Cocks, 2013). Scotese's Gondwana reconstructions (http://www.globalgeology.com) show a broad mountainous area over what is now northern Mozambique and eastern Zimbabwe during the Permo-Triassic. These mountains are the eroded remnants of the Trans-Gondwana Mountain Belt, and represent the logical source area for these west-flowing river systems. Isostatic uplift as ice sheets melted may explain the low-energy of the Ecca fluvio-lacustrine system.

Upper Karoo high-energy fluviatile event

The Cãdzi Formation that unconformably overlies the Matinde Formation in the Cabora Rift-basin is dominated by well exposed, cross bedded, thick to very thickly bedded arkosic and pebbly sandstones that are up to about 2300 m in thickness (Plate 1). These sandstones (and sandstones from the Escarpment Grits and Angwa Sandstone Formation) are interpreted as high-energy, fluviatile sediments (Broderick, 1990; Afonso et al., 1998; Banks et al., 1995; Key and Barclay, 2012; Barclay, 2013a; b). Lateral east to west facies and thickness changes are recognised in the Upper Karoo at Formation level from thick eastern (proximal facies) sandstones in the Cabora Bassa Rift-basin (Cãdzi Formation), and thinner (<400 m) sandstones of Upper Karoo sandstone-dominated sequences in the Mid-Zambezi Basin (Ait-Kaci Ahmed, 2003) to interbedded sandstones and mudstones (distal facies) in the Kalahari Basin (e.g. Smith, 1984; Johnson et al., 1996; 2006; Catuneanu et al., 2005). Smith (1984) records Upper Karoo (Pandamatenga Formation) high-energy, fluviatile sandstone beds in north-eastern Botswana near the margin of the Kalahari Basin.

A common feature of all Cãdzi Formation sandstone exposures (that can cover several thousand square metres in area as rock pavements and cliffs) is the presence of stacked sandstone beds, all with unidirectional, large-scale, mostly planar cross beds (Plate 1). Palaeo-current readings measured in the Chicõa-Mecúcoè Sub-basin (from ten large exposure areas; Key, 2012) in the area between 31°51' and 31°38'E and 15°44' and 15°47'S show west-directed currents in the arc between 240° and 300° (i.e. parallel to the present course of the Zambezi River in this area). These data agree with previous west-directed current directions found further to the west in Zimbabwe and Zambia (Shoko, 1998; references in Yemane and Kelts, 1990; Ait-Kaci Ahmed, 2003). Oesterlen and Millsteed (1994) describe the geology of the westernmost part of the Cabora Bassa Rift-basin in eastern Zimbabwe. Their 33 cross-lamination and cross-bedding current bedding readings show strong (almost unidirectional) west-directed currents for fluviatile sandstones of the Angwa Sandstone Formation in the western (Zimbabwe) region of the Cabora Bassa Basin.

Current bedding readings from large exposures of Cãdzi Formation sandstones in the northwest to southeast trending Moatize-Minjova (between 33°36' and 33°45'E and 16°15' and 16°22'S; Barclay, 2013b) and Sanângoè-Mefidezi Sub-basins (between 34°15' and 34°38'E and 16°20' and 16°30'S; Key and Barclay, 2012) show unidirectional northwesterly trending currents. The Moatize-Minjova Sub-basin readings are from exposures immediately adjacent to the northwest to southeast trending Zambezi River. However, the readings from the Sanângoè-Mefidezi Sub-basin are west of the present course of the Zambezi River (Figure 3) and highlight the spread of the westerly flowing Upper Karoo high-energy river system.

Upper Karoo aeolian and volcanic event

Upper Karoo strata in the rift-basins of eastern and central Africa are unconformably succeeded by Triassic aeolian/fluviatile sands deposited as the climate became hotter and more arid (e.g. Mountney and Howell, 2000; Bordy and Catuneanu 2002; Ait-Kaci Ahmed, 2003; Myers et al., 2011; Torsvik and Cocks, 2013). It is possible that flow of the Upper Karoo rivers became seasonal or dried up during this period. A major Jurassic (Stormberg Group) volcanic event lasted from about 184 to 173 Ma (Duncan et al., 1997; Guillocheau et al., 2013a; b) and marks the end of the Karoo Supergroup (Tables 1 and 2). Karoo flood basalts formed a carapace up to several thousand metres in thickness over southern Africa in early Jurassic times (about 184 to 173 Ma; Duncan et al., 1997; Guillocheau et al., 2013a; b) and would have had a major impact on the landscape and river systems of Western Gondwana. However, end-Karoo volcanism in the Cabora Bassa Rift-basin was confined to localised volcanic centres with emanating dykes and sheets (Lächelt 2004; GTK Consortium 2006; Key, 2011b; 2012; Key and Barclay 2013) and may not have had such a drastic effect on rivers within this rift-basin. Nevertheless, the flood basalts covered the lower part of the Proto-Zambezi River system (in what is now central Botswana; Key and Ayres, 1998) and would have effectively obliterated this part of the river system. The west-northwest to east-southeast trending Karoo dyke swarm (Reeves and Hutchins, 1975) across northern Botswana also cut across the buried lower Proto-Zambezi to effectively dam any groundwater flow.

A northeast to southwest trending sub-Kalahari (pre-Miocene?) valley is incised into the extensive basalt cover that straddles the Botswana-Zimbabwe border, with its orientation broadly co-linear with the Luangwa-Gwembe Rift, and the inferred extension of the rift into the Makgadikgadi Pans area of Botswana (Figure 9 of Moore and Larkin, 2001; Moore and Cotterill, 2010). Thus, very counter-intuitively, the basalt cap does not seem to have resulted in a major drainage disruption in this area, although an accumulation of thin basalt flows were widespread across the Middle Zambezi valley (Stagman and Harrison, 1978). This suggests that lines of rifting in the basement were transmitted upwards through the basalt capping. The reasons for the persistence of this drainage system, controlled by pre-basalt rift lines, are an important focus of on-going research.

Plate 1. *Cādzi Formation field photographs. (**A**) Cliffs of Cādzi Formation sandstones; (**B**) Very thickly bedded sandstones; (**C**) Pebbly, cross bedded sandstones; (**D**) High-angle cross bedded sandstones. A and B from the south side of Lake Cabora Bassa, Chicoa-Mecùcoè Sub-basin; C and D from the Moatize-Minjova Sub-basin close to the Malawi border.*

Summary of the geological evidence

Evidence presented in the previous sections demonstrates that a large westerly and southwesterly flowing river system dominated the drainage across West Gondwana through Permo-Jurassic times. The upper and middle reaches of this river followed the same rift-controlled course as the modern Zambezi River through western and central-eastern Mozambique and eastern Zimbabwe. Previously, Oesterlen and Millsteed (1994) refer to a west-flowing Proto-Zambezi River during deposition of the Forest Sandstone sediments in Late Triassic – Early Jurassic times in the western part of the Cabora Bassa Rift-basin. Tavener-Smith (1956) indicated that post-coal Karoo sedimentation in the Gwembe Coalfield of Zambia took place either side of the present Zambezi River course. The river system evolved from Lower Karoo rift-bounded lakes and low-energy rivers into high-energy, sinuous Upper Karoo rivers (e.g. Johnson et al., 1998).

Bounding faults to the Cabora Bassa Rift-basin exhibit a propensity for tectonic reactivation (that commenced in Early Permian times) of precursor ductile shear zones in the underlying Precambrian basement. Movements on tensional listric faults recurred throughout the Permo-Triassic and into the Jurassic, and they continued into the Cretaceous as Gondwana started to fragment. However, Africa eventually separated from the rest of West Gondwana along new fault lines that cut obliquely across all older faults. This is clearly shown by the north-south trend of Mozambique's coastline compared to the approximately east to west tectonic 'grain' of Mozambique's Precambrian basement (e.g. Bingen et al., 2009) and the approximately northwest to southeast trend of the Karoo rift faults.

In summary, the westward direction of the Proto-Zambezi River system in the Permo-Triassic is indicated by: (1) current bedding readings from Upper Karoo sandstones and (2) regional facies change from proximal eastern sediments to distal western sediments within the Cabora Bassa and Mid-Zambezi Basin and Kalahari Basin, and both bodies of evidence agree with (3) the Early Permian palaeo-geographical reconstruction of southern Africa (Smith, 1984; Reeves, 2009; 2013; de Wit, 1999; Guillocheau et al., 2013a; b). These reconstructions identify a western endorheic delta, in what is now southwestern Botswana and northwestern South Africa, fed by a major river system with its source in northern Mozambique. We propose that its headwaters drained the eroded relict relief of the EAAO mountain belt (which was also the likely accumulation zone of Dwyka glaciers). Further indications of an early west-directed river system are preserved in the orientation of major tributaries of the modern Zambezi River; the Chambeshi and Kafue Rivers occupy inherited vestiges of a continuous, southwesterly flowing major river system (Moore and Cotterill, 2010) that was originally in accordance with a west-directed Proto-Zambezi River (Figure 1).

Visser (1987) identified an east-west oriented glacial valley (the Chipise Valley) exploited by the east-flowing section of the Limpopo, which forms the modern Zimbabwe-South Africa border (Figure 1). Ice flow along this valley was to the west (Visser, 1987), suggesting that its source also lay in the EAAO mountain belt.

A recent review (Roberts et al, 2012b) in revising the timing of early evolution of the western branch of the East African Rift postulated that a major northwesterly oriented river flowed, via the Rukwa Rift, into the mid-Cretaceous Congo Basin. Their drainage reconstruction is supported by palaeo-current measurements and zircon provenance studies, but these authors do not discuss the origin of this drainage line. Drawing analogy with the west-flowing Proto-Zambezi, we propose it is a relic of an earlier drainage system draining to the west from its source headwaters on the Trans-Gondwana Mountain Belt.

However, on the south-eastern side of the Rukwa Rift, at the northeastern extremity of the Luangwa Rift, palaeo-currents in the Tukuyu mid-Cretaceous section are to the east (Roberts et al., 2012b). This suggests a mid-Cretaceous watershed already separated the northwesterly flowing Proto-Congo drainage line of the Rukwa Rift from the main Luangwa valley. The Luangwa appears to have maintained a south-westerly course since at least the earliest Upper Permian (Banks et al., 1995; Tiercelin and Lezzar, 2002). Such a course not only accords with a west-flowing drainage line, but it is also consistent with the interpretation that the Luangwa was a major north bank tributary of the west-flowing Proto-Zambezi (Moore and Larkin; 2001); (Figure 1). Kalahari isopachs in Zimbabwe's Hwange area delineate a deep southwesterly directed valley, interpreted to mark the continuation of this southwest to northeast orientated Luangwa-Gwembe rift system into Botswana (Moore and Larkin, 2001).

The African evolution of the Zambezi River

Rift flank uplift associated with the disruption of Gondwana would have initiated a major reorganization of the entire Karoo drainage system including the Proto-Zambezi River (Cox, 1989; Moore and Blenkinsop, 2002). Published data on the uplift (e.g. Emmel et al., 2011) indicate that it may have lasted, albeit intermittently, from the start of the Triassic (about 250 Ma) until well into Cretaceous times (about 113 Ma). Plate reconstruction by Reeves (2009) shows the lower Zambezi River flowing in an easterly direction at about 165 Ma into the open sea created by separation of Dronning Maud Land from southern Africa. However, precursors of the modern Chambeshi-Kafue River system (with the upper Zambezi as a right-bank tributary) and Luangwa-Gwembe River system were then likely parts of a major southwesterly flowing drainage systems between about 165 and 135 Ma (Moore and Blenkinsop, 2002). The detailed configuration of this early upper Zambezi drainage system is speculative, as evidence of former drainage lines is masked by the Kalahari Formation, which covers much of south-central Africa; but a possible former link to the Orange River

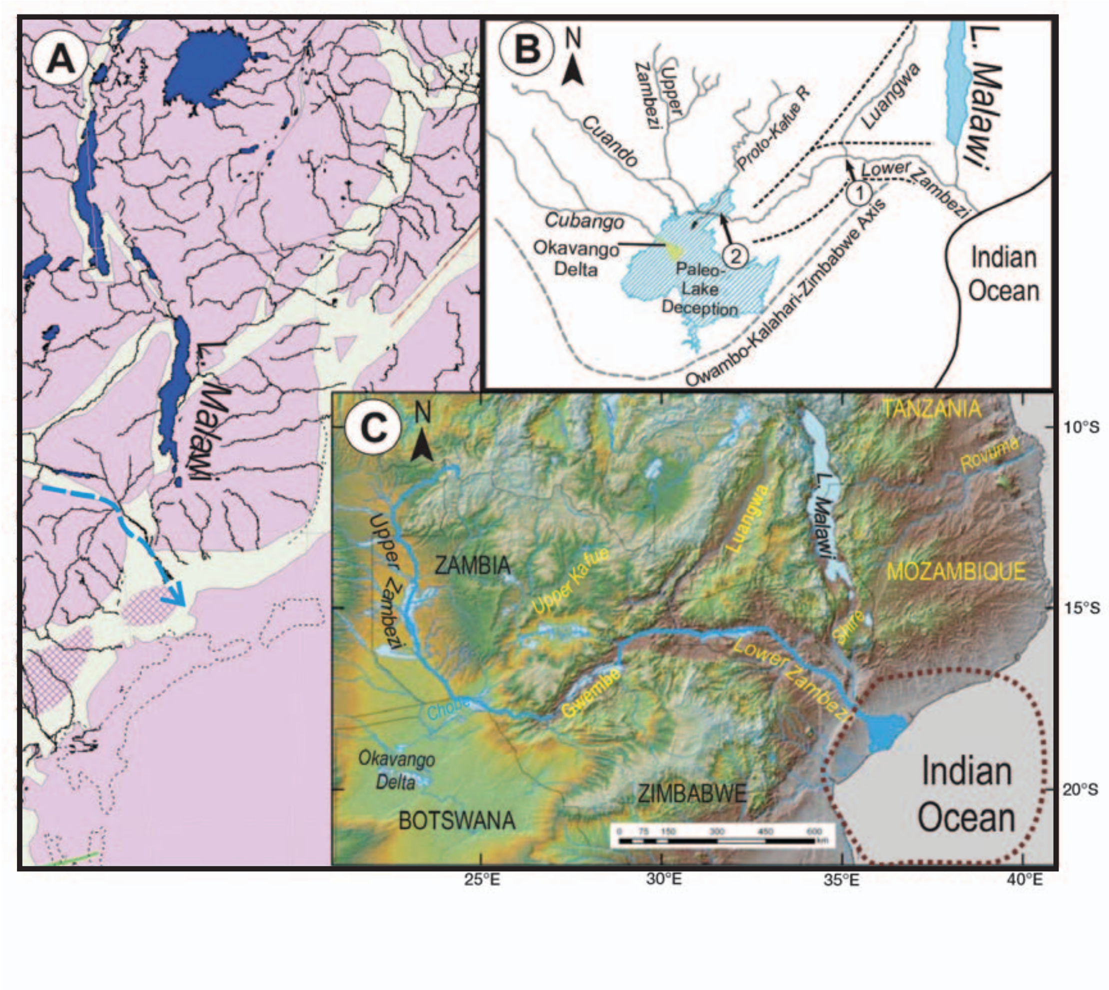

Figure 4. *The evolution of the Zambezi River system: (**A**) at about 180 Ma, from Reeves (2009); (**B**) from mid to late Cenozoic, depicting sequential capture of the Luangwa in the Oligocene (**arrow 1**) and piracy of Kalahari Plateau drainage by the Early Pleistocene (**arrow 2**); and (**C**) modern topology indicating the approximate extent of the Zambezi delta.*

has previously been suggested by Wellington (1955). Rift flank uplift and the resultant change of the continental palaeo-slope associated with the opening of the Atlantic Ocean (about 125 Ma) initiated a further major drainage reorganization, including river capture south of the Zambezi River system into the headwaters of the Limpopo River, which flowed eastwards into the Indian Ocean (Moore and Larkin, 2001; Moore and Blenkinsop, 2002).

Opening of the Indian Ocean lowered the base level that initiated headward erosion by the lower Zambezi River system, exploiting the lines of weakness in the grabens that today bound the modern Zambezi River. This is consistent with the conclusion by Bond (1970) that the modern Zambezi River is exhuming pre-Karoo valleys. Capture of the Cabora Bassa Basin and Luangwa River in the Oligocene by the Zambezi (Figure 4B) resulted in a major headwater expansion (Moore and Larkin, 2001). This, coupled with the marked lowering of the erosional base level of the Luangwa River, would have dramatically increased erosion rates. It could, in turn, account for the major increase in sediment supply to the Zambezi Delta at the end of the Palaeogene recognized by Walford et al (2005) and Guillocheau et al., (2013a; b). The resultant enhanced headward erosion of the now predatory Lower Zambezi sequentially captured the Mana Pools and Gwembe basins (Figure 1) of the originally west-flowing Proto-Zambezi River. Deep gorges connecting these basins (upstream respectively, of the Cabora Bassa, Mupata and Kariba Gorges; Figure 1) are interpreted to mark the locations of sequential captures of the Cabora Bassa, Mana Pools and Gwembe rift-bound basins (Moore and Larkin, 2001) by headward erosion of lower Zambezi tributaries (Figure 1). These piracies progressively diverted vestiges of the Proto-Zambezi to flow east into the expanding catchment of the Lower Zambezi.

This expansion of the modern Zambezi's catchments further explains the geomorphological character of the regional landscape, notably in the different valley forms of the smaller tributaries (e.g. Angwa, Lusemfwa, Manyame, Rukomechi, Sanyati and Sapi; Figure 1) compared to the flat-bottomed basins occupied by the Luangwa and Mid-Zambezi Rivers. This contrast is most striking where these tributaries have incised steep, deeply narrow gorges into the more erosion resistant Proterozoic rocks of the escarpments bounding the Luangwa and Zambezi gorges. Downstream of their gorges, these tributaries have contributed to exhuming graben of Karoo sediments originally deeply infilled by the Proto-Zambezi. This contrast between these valleys is attributed to differential resistance of the underlying lithology to the eroding rivers responding to the lowered base level, and it has likely been accentuated by Late Cenozoic horst uplift in the case of the Luangwa's tributaries.

Late Palaeogene continental flexuring along the arcuate Ovambo-Kalahari-Zimbabwe (OKZ) axis severed the former link between the Limpopo and Upper Zambezi headwaters (Moore et al., 2009a; Figure 4B). The consequence was that the latter became an endorheic drainage system which supplied sediment to the Kalahari Basin. The OKZ Axis was coeval with a major reorganization of the oceanic spreading regime around southern Africa (Moore et al., 2009a). It is possible that stresses linked to the OKZ flexure also reactivated former Karoo rift zones, thus facilitating headward erosion of the lower Zambezi along rift-bounding faults. A further possible consequence of the flexure may have been the propagation of the East African Rift System (EARS) to the southwest into northern Botswana, ultimately resulting in the initiation of a major inland lake system in the Makgadikgadi Basin (Moore et al., 2012; Figure 4B).

The supply of sediment to the Kalahari Basin was significantly disrupted by capture of the Chambeshi-Kafue-Upper Zambezi precursors (collectively the Palaeo-Chambeshi) by the middle Zambezi in the late Pliocene or early Pleistocene (Moore et al., 2012; Figure 4B). The modern Okavango River is the only remaining vestige of the original endorheic system. Capture of the Upper Chambeshi by the Luapula River (Congo System) in the Pleistocene resulted in a major reduction in the headwaters of the modern Zambezi network. A further change was the severance of the link between the Kafue and upper Zambezi, followed by capture of the former by a tributary of the Mid-Zambezi (Moore et al., 2012; Figure 4B).

Implications for longevity of major river systems and hydrocarbon potential of major sedimentary basins off Africa's eastern coast

The estimated combined age of about 280 million years for the Proto-Zambezi and Zambezi Rivers is comparable to that of the Proto-Mississippi and Mississippi Rivers, identified as one of the world's oldest persistent drainage systems with a maximum age of ~260 Ma (Potter and Hamblin, 2006). The Proto-Zambezi and its major tributaries exploited Dwyka (uppermost Carboniferous – earliest Permian) glacial rift-valleys, which have also been inherited by modern rivers. The Luangwa River has likely maintained its south-westerly flow direction for about 280 million years (Banks et al., 1995; Tiercelin and Lezzar, 2002).

These intricacies of drainage evolution hold important implications for exploration; the reversal in the flow directions of the Proto-Zambezi and Zambezi Rivers means there are not likely to be any Karoo deltaic sediments at the base of the present Zambezi River delta. Permian palaeogeographic reconstructions of Gondwana also show that what is now the south-east coast of Africa lay within West Gondwana. However, basal Karoo strata are suggested from interpretations of seismic investigations in the major sedimentary basins to the north, including the Rovuma Basin where World-class gas deposits have now been found, albeit in post-Karoo sequences (Salman and Abdula, 1995). Palaeogeographic reconstructions of Gondwana indicate that East Africa lay within West Gondwana during the Permian. Therefore any Karoo sediments in this area can only have been deposited within inland basins. Rivers now draining eastwards into the northern offshore basins (e.g. the Rovuma and Rufiji Rivers) are short relative to the Zambezi River, and they are also younger because their source areas formed by uplift associated with the Cenozoic EARS. Prior to this rift-flank uplift the river systems in this area flowed westwards (Roberts et al., 2012b, Figures 2 and 4). It is clearly pertinent to hydrocarbon exploration in these offshore basins to refine the exact fit of the fragmenting parts of Gondwana during Karoo times, in order to exactly define the dimensions of any rift basins. It is possible that there are lacustrine (but not deltaic) Karoo sediments at the base of the Zambezi River delta.

The synthesis of evidence attesting to the longevity of Zambezi River has the following important wider implications for the evolution of passive plate margins:

- The fracture system along what is now Mozambique's eastern coastline associated with the Jurassic break-away of Africa from East Gondwana cuts across pre-existing (Precambrian and Karoo) lines of weakness, and it did not utilise them in defining the African coastline. For example, the north to south trending fault that defines the western margin of the Rovuma Basin cuts sharply across the predominant east to west tectonic grain of the Precambrian foreland (Key et al., 2008). However, uplift of the African Plate associated with lateral plate movement did re-activate brittle (uppermost crust) Mesozoic faults up to 500 km away from the plate margin, such as bounding faults along Karoo rift-basins with a previous history of tectonic re-activation (Key et al., 2007).
- These lines of evidence hold broad application to reconstruct details of ancient plate configurations, especially as they confirm that major rift-basins affected by crustal re-adjustments, during the

formation of new passive plate margins, can survive plate separation through re-activation of their bounding faults. However wider (sub-continental) changes in topography can reverse the drainage directions in these rift-basins. The survival of major rift-basins against new passive plate boundaries preserves evidence that can possibly match such systems across separated continental plates. This presents another means of reconstructing former supercontinents.

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