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The drainage of Africa since the Cretaceous

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Abstract

Much of the drainage of Africa is relatively youthful. Many of its major rivers have shown substantial changes in their courses since the break up of Gondwanaland in the Cretaceous. In addition, many of the rivers have distinctive morphological characteristics such as inland deltas, cataracts and elbows of capture. Tectonic and climatic changes, including the development of the East African Rift System and the aridification of the Quaternary, help to explain the nature of these rivers. The history of the Saharan rivers, the Niger, the Nile, the Congo, the Cunene, the Zambezi, the Limpopo and the Orange, is reviewed.

Keywords: Africa; Drainage; Post-Cretaceous; Tectonics; Climate change

1. Introduction

Many of the rivers of Africa have a range of intriguing characteristics that indicate that they have had complex histories involving shifts in the nature of their catchments and courses, particularly since the splitting of Gondwanaland began in the early Cretaceous. Nearly all of them are characterized by falls (e.g. the Zambezi at Victoria Falls and Caborra Bassa, and the Orange at Augrabies) and cataracts (e.g. the Nile at Aswan, and the Congo at Stanley Pool), some of them are linked by spillways (e.g. the Zambezi and the northern Botswana drainage), many of them drain into and out of large depressions (e.g. the Nile out of the Sudd), some have inland deltas (e.g. the Niger and the Okavango), some show evidence of capture or piracy (as on the Cunene), and some of them have become entangled in dune fields (e.g. the Niger, Senegal and the Zambezi). In addition, some drainage systems, such as those of the northern Sahara or the *mekgacha* of the Kalahari, have become defunct. These characteristics reflect the long and varied climatic and tectonic history of the continent and its distinctive topographic arrangement.

Unlike most other continents Africa is characterized by passive rather than active plate margins and by a dominance of basins, faults, rifts and topographic swells rather than by compressional mountains (Holmes, 1944; Summerfield, 1996; Doucouré and de Wit, 2003). The Atlas Mountains are the only major Cenozoic exception to this. There are, however, a

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number of intraplate hotspots in Africa that have been associated with Cenozoic doming and volcanism, including those of Ahaggar, Tibesti, Jebel Marra and Mt. Cameroon (King and Ritsema, 2000). These young mantle plumes have been largely responsible for the development of the basin and swell topography, which is such a unique feature of the interior of the African continent and which is so crucial in terms of drainage development (Fig. 1a). In addition, the coastal margins of much of Africa have been affected by a coastal upwarp, which has its clearest manifestation in the Great Escarpment of southern Africa. This marginal upwarp accounts for the characteristic hypsometry of Africa's drainage basins, in which only a very small proportion of the area of each basin is at low elevations (Summerfield, 1991). Rifting has been another fundamental feature of the evolution of Africa, particularly in East Africa (Fig. 1b).

The key events in the development of the setting of African drainage basins have been:

(1) Opening of the South Atlantic (started ca. 150 Ma)
(2) Paraná-Etendeka volcanism (138–127 Ma)
(3) Final separation of Africa from S. America (ca. 100 Ma)

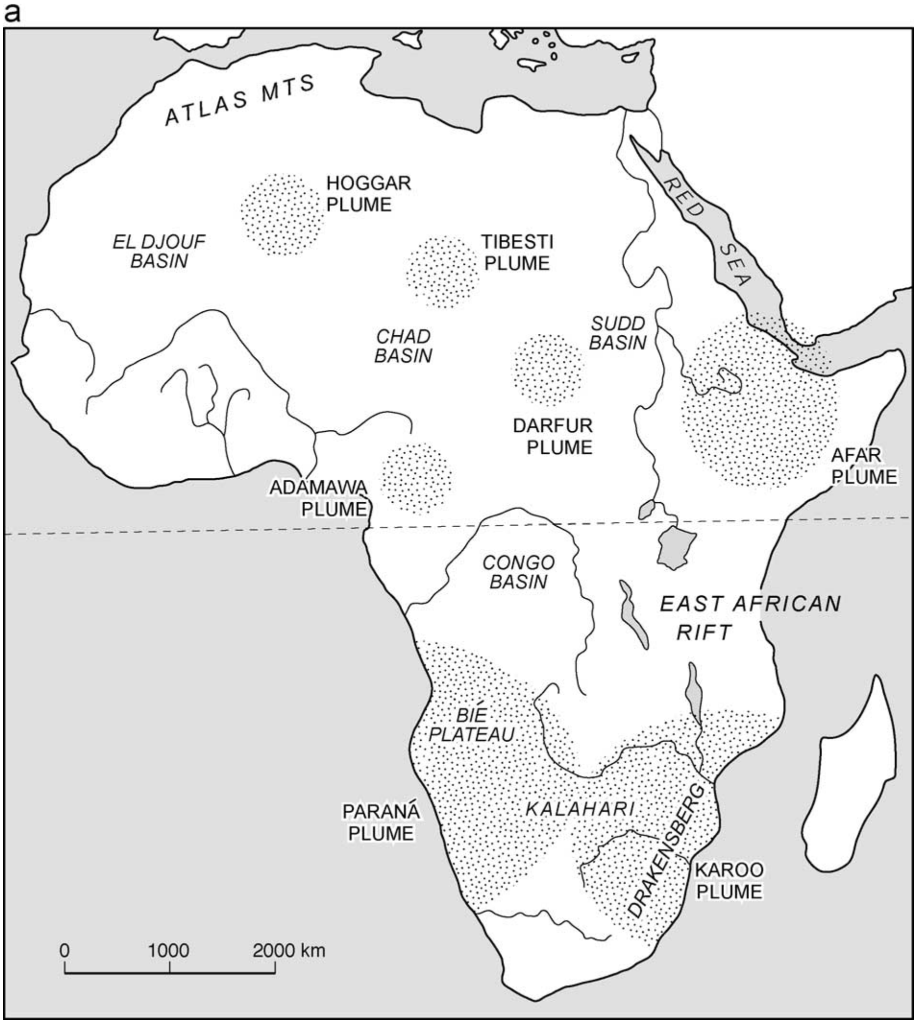

Fig. 1. (a) Some of the major plumes and basins of Africa. (b) The main rifts of East Africa.

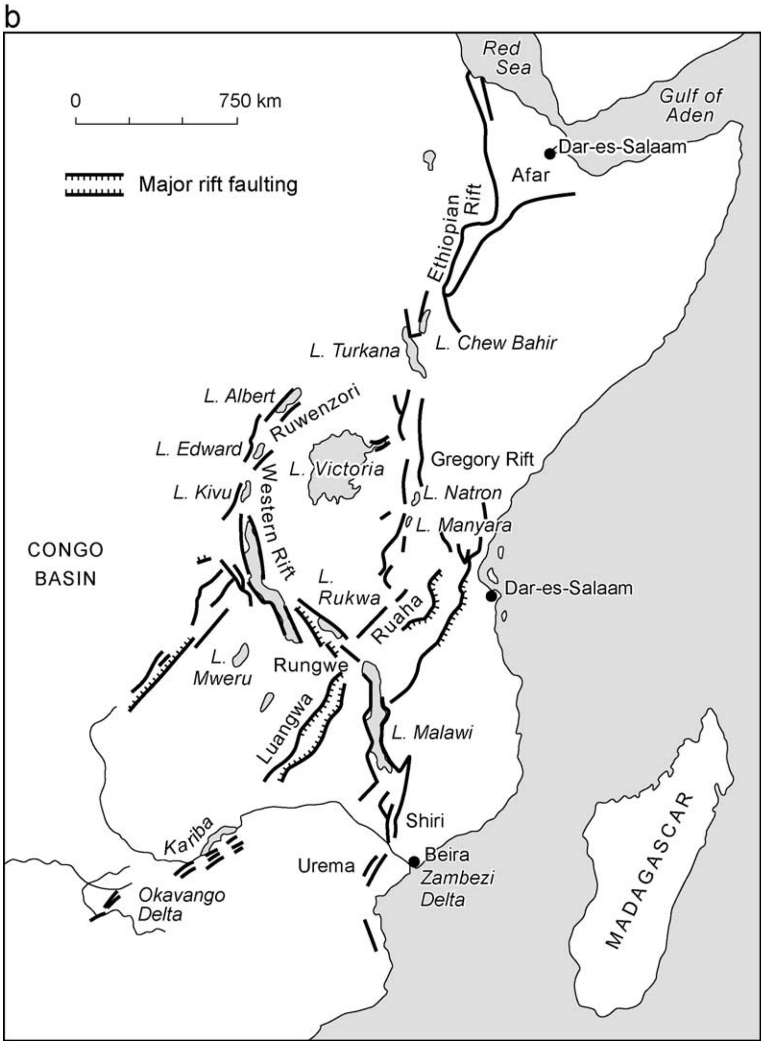

Fig. 1 (*continued*).

(4) Start of eruption of Ethiopian and E. African plateaus and arrival of Afar Plume head at lithosphere (45 Ma)
(5) Start of E. African rifts and Red Sea rifting (30 Ma)
(6) Uplift of Red Sea margins begins (13.8 Ma) and Gulf of Aden opens (10 Ma)
(7) Messinian salinity crisis and desiccation of the Mediterranean (6 Ma)
(8) Start of Pleistocene aridity (ca. 2.4 Ma)

In this paper, the drainage histories of some of the major basins are discussed and are related to the tectonic and climatic vicissitudes of the continent. What emerges from this is confirmation of the views of early researchers such as Passarge (1904, p. 637) and Falconer (1911, p. 241) that many of the river courses of Africa are remarkably youthful. Fig. 2 shows the locations of the present major rivers of Africa and some of the previous routes that have been postulated for them.

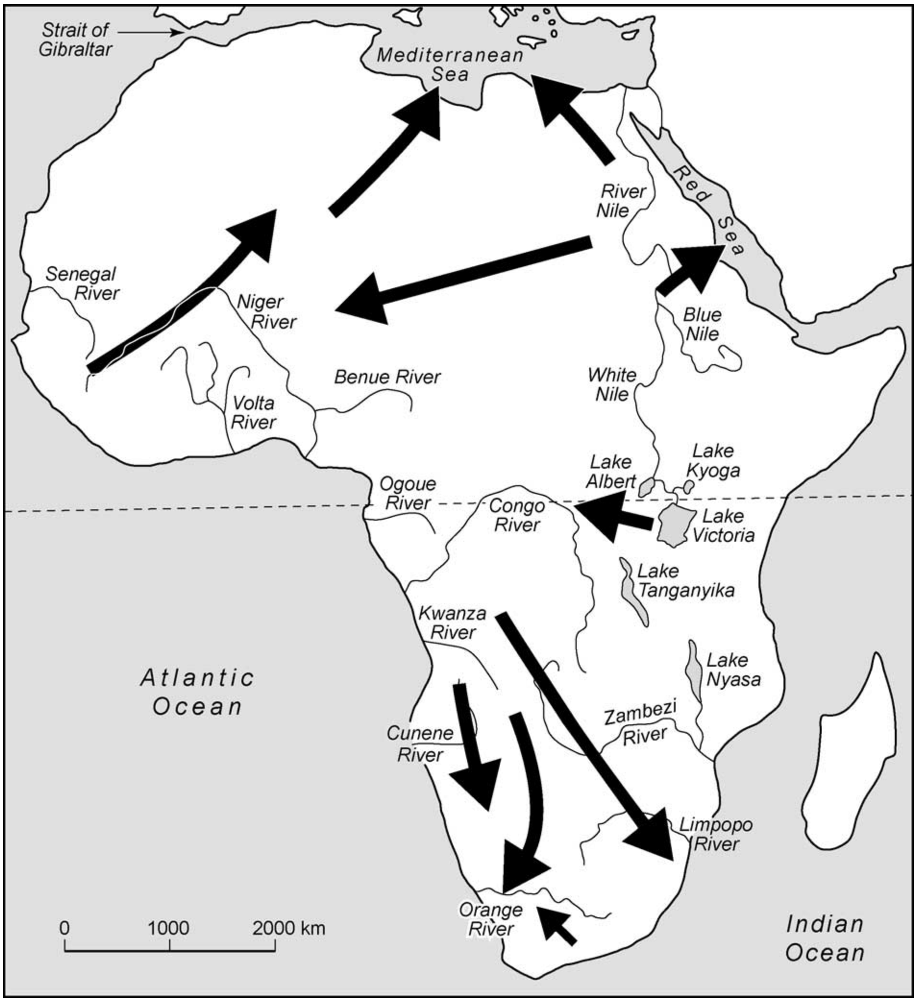

Fig. 2. Major drainage lines of Africa at the present day together with some of the major former directions of drainage (shown by arrows) discussed in this paper.

Some of the scenarios for drainage development presented in this paper are speculative both with regards to their dating and to their very existence, but in recent years several developments have taken place that have provided a greater degree of certainty as to what has happened: remote sensing has enabled certain ancient river courses to be identified; radiometric dates have become available for major phases of volcanic activity and rifting; offshore cores, sonar and seismic studies have indicated the fluvial source areas of depocentres; tracer studies have been conducted in association with mineral exploration (e.g. for diamonds); and plate tectonic theory has provided a greater understanding of crustal instability.

2. North Saharan rivers

During the Neogene, uplift occurred in parts of the Sahara (e.g. Tibesti and the Hoggar), and the climate was sufficiently moist to enable large drainage systems to develop. During the Miocene, four main drainage basins were operational in the North Sahara: the Eonile, the Eosahabi, the Gabes and the Chad (Griffin, 2002). Of these, the Eosahabi and Gabes systems are now essentially inactive. The former covered an area of around 0.9 million km^2 and drained northwards into the Gulf of Sirt. The great diversity of the fauna (including crocodiles) and the nature of the flora suggest it was a large river which suffered disruption and partial obliteration as a result of increasing aridity in Pliocene and Pleistocene times. The Gabes system was even larger, draining 1.1 million km^2 and entering the Gulf of Gabes. It passed through what are currently closed depressions (e.g. the Chott Melrhir and Chott el Jerid), but became disrupted after about 4.6 Ma, when rainfall diminished in the area. In addition, offshore seismic studies in the Cape Bojador Slope also reveal that during the Miocene substantial rivers flowed out of the Western Sahara towards the Atlantic Ocean, depositing deltas and eroding pre-existing sediments (Pickford, 2000). In the eastern Sahara, a large system flowed from Tibesti to Kufra (Pachur, 1993).

3. The Niger

The Niger (basin area 2.26 million km^2) is a remarkable river. It rises at an altitude of 800 m in the Fouta Djallon plateau of Guinea, a mere 250 km east of the Atlantic coastline in Sierra Leone and Liberia. It then flows in a great arc (Fig. 3) that takes it over a distance of 4200 km to reach the sea in Nigeria. Initially, it flows towards the Sahara and near Timbuktu passes through an inland delta. Then, at Tosaye, it suddenly changes course and heads SSE through Niger and into Nigeria. It is possible that the Niger used to flow northeastwards into the Sahara, creating a great lake in the Azaouad (Urvoy, 1942) and that it has only recently flowed past the sill at Tosaye. It is probable that its northward flow was blocked by dune construction during arid phases of the Pleistocene. In wetter phases, a lake formed which in time spilled over the Tosaye sill to join the lower Niger system (Tricart, 1965; Jacobberger, 1981; McIntosh, 1983). Large parts of the Niger drainage catchment, as Fig. 3 shows, are currently inactive, but during moist phases they were more fully active and at high stages Lake Chad overflowed over the Bongor Spillway into the Benue and thence into the Niger (Talbot, 1980). During wet episodes, drainage ran from the southwestern slopes of the Ennedi massif into Lake Megachad and thence over the spillway. This was a total distance of over 2500 km (Burke, 1996). It has also been argued, though not universally accepted, that the Niger was in the Tertiary fed by a major Trans-African palaeodrainage system arising in Egypt and Sudan (McCauley et al., 1982) and which has now been captured by the growth of the Nile system. It is possible this phase of augmented discharge could help to explain the anomalously large size of the Niger delta fan. On the other hand, the Niger delta, Africa's largest, is old. From ca. 80 to ca. 35 Ma, it was fed by a major valley that occupied the site of the Benue Rift, which had formed initially at ca. 140 Ma with the break up of Gondwanaland.

4. The Nile

The Nile is another extraordinary river. It is nearly 7000 km long (and thus the longest river in the world), drains some 3.2 million km^2 and stretches approximately north to south over 35° of latitude. It manages to flow through one of the biggest tracts of severe aridity on Earth, has numerous cataracts and falls and yet has an immensely gentle gradient in its lowest portion. Aswan, almost 1000 km from the sea, lies at an altitude of only 93 m above present sea-level. In spite of its great length and large catchment area, its discharge is very small by the standards of other rivers of its size. Moreover, as Said (1981, p. 6) has pointed out, the Nile negotiates its way through five regions which differ from one another in terms of geological history and structure: the great Lake Plateau of Central Africa, the Sudd and Central Sudan, the Ethiopian Highlands, the Cataract tract from Khartoum to Aswan, and the Egyptian region down to the Delta and the Mediterranean.

The Egyptian Nile as we see it today is possibly a young river in geological terms. It is only recently that its diverse component tracts have been linked up and that it has followed its present course through the eastern Sahara. As Issawi and McCauley (1992) have written:

> Egypt, during the Cenozoic Era, was drained not by a single master stream but by a succession of at least three different, major drainage systems that competed

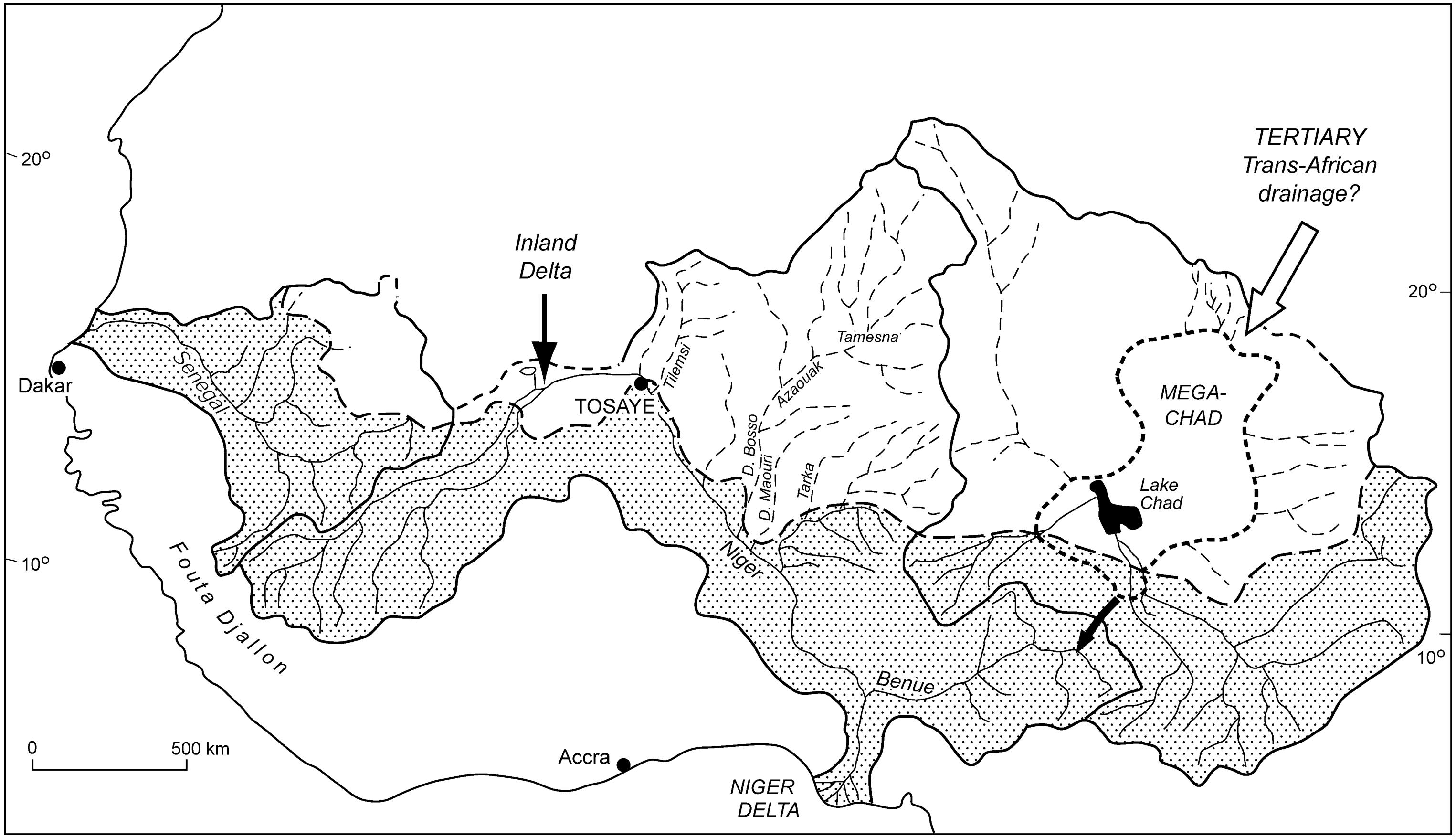

Fig. 3. The maximum potential catchment areas of the Senegal and Niger–Benue systems. Areas that currently contribute to runoff are dotted. During periods of maximum humidity (e.g. the early to mid-Holocene), the whole of the catchments may have been active. Overflow from the Chad Basin reached the Benue along the route indicated by the arrow (modified after Goudie, 2002, Fig. 4.18).

for survival by means of gradient advantage. This competition took place in response to tectonic uplifts and sea-level changes during the interval between the retreat of the Tethys Sea in late Eocene time (40 Ma [million years ago]) and the birth of the modern Nile during the late Pleistocene (~25 ka).

They present a possible model of Saharan Nile evolution (Table 1). The first stage called the Gilf system consisted of a northward flowing consequent stream that followed the Tethys Sea as it retreated, creating newly emergent land in Egypt. It also consisted of some streams that formed on the flanks of the Red Sea region towards the end of the Eocene. The form of the Gilf system is shown in Fig. 4a. It is probable that the climate during the Tertiary was relatively humid and provided adequate run-off to feed the system and to promote karst formation on the Eocene limestones of the Western desert. This system operated from ca. 40 to 24 million years ago.

The second stage, termed the Qena system, was caused by major tectonic activity in the Red Sea area. This caused a reversal of drainage to occur with a large river flowing southwards towards Aswan and the Sudan. The south-trending Wadi Qena is a relict of this time and this helps to explain its curious directional geometry with respect to today's Nile. The state of the rivers during the Qena system times is shown in Fig. 4b. It was at this time that catastrophic flooding may have created some major erosional flutes and gravel spreads in the Western Desert (Brookes, 2001).

Table 1
Issawi and McCauley's stages of Saharan Nile evolution

1. Oldest—the Gilf system
Consists of north-flowing consequent streams that followed the retreating Tethys Sea across the newly emerging lands of Egypt and streams that formed on the flanks of the Red Sea region towards the *end of Eocene.*
2. Middle—the Qena
Major south-flowing subsequent stream that developed along the dip slope of zone of intensified uplift in the Red Sea Range during the *early Miocene.* Flowed to Sudan basin. Confined to west by retreating scarp of the Limestone Plateau and on the east by the uplifted rocks of the Red Sea Range.
3. Youngest—the Nile system
Came into existence as a result of the drop in Mediterranean sea-level in the late Miocene. Formerly local drainage eroded headword into Limestone Plateau. Captured Qena system and reversed its flow from south to north.
4. Pliocene flooding
After reopening of Straits of Gibraltar in early Pliocene sea-level rose to at least 125 m. Estuary extended to Aswan (>900 km inland).
5. Pleistocene sea-level change
(including Flandrian transgression)

The third stage, termed the Nile system (Fig. 4c), was associated with base level changes in the Mediterranean basin. In Messinian time, round about 6 million years ago, the Mediterranean dried up for about 600,000 years (Krijgsman et al., 1999) because of closure of the Straits of Gibraltar. Base level dropped by 1000 m or more. Down cutting and headward erosion became dominant processes and the Eonile, as it is called, incised a deep gorge four times larger than the Grand Canyon of the Colorado in the USA. Because of its gradient advantage, it captured the south-flowing Qena system and became the first north-flowing river system that extended the length of Egypt to the Mediterranean.

In the early Pliocene, sea-level rose to at least 125 m so that an estuary or ria extended more than 900 km inland, reaching Aswan. This is termed the Gulf phase. The subsequent stages of Nile evolution have been explored by Said (1981). During the Paleonile phase a local river occupied and filled the Gulf with sediments. Following a dry phase, when the Nile ceased flowing, the Prenile developed. This mid-Pleistocene event appears to have been the first time that a mighty river with a distant source reached Egypt. It drew some of its discharge from Ethiopia when the Atbara (and possibly the Blue Nile) pushed their way into Egypt across the Nubian Swell by a series of cataracts. This was caused by tilting in the Ethiopian Highlands so that drainage was directed towards the Nile rather than the Red Sea. Later still, during the Neonile phase, the link with the Central Africa lake region was established, but during the Pleistocene dry phases the Nile was often seasonal rather than the perennial river it is today. This was, for example, the case between ca. 20,000 and 12,500 years BP (Adamson et al., 1980; Williams and Adamson, 1982).

Conversely, during more humid phases, like the early Holocene, its flow was augmented by now extinct tributaries such as the Wadi Howar, an 800-km long watercourse that rose in the region between Jebel Marra and Ennedi (Pachur and Kröpelin, 1987).

In the 1980s, there was speculation based on analysis of remotely sensed radar data that a Trans-

African drainage system, originating along the western margins of the Red Sea hills in Egypt, Sudan and Ethiopia, found its way across to the Atlantic via Lake Chad. (McCauley et al., 1982), though this was criticized by Burke and Wells (1989) and has also been challenged by Robinson et al. (2000), who believed the so-called radar rivers of the Selima Sand Sheet did not flow south westwards towards Chad but northeast and eastnortheast towards Kharga.

Further towards it source, the Nile owes much of its character to the uplift of the Ethiopian Highlands and the development of the East African lakes. In northwest Ethiopia, the volcanic plateau is a zone of high relief that forms the headwaters of both the Blue Nile and the Tekeze—the main tributaries (70% for water and >95% for the suspended load) of the Nile. The plateau results from regional basement uplift and lava flow accumulation, associated with the development of the Afar plume (Pik et al., 2003). The volcanic activity was initiated in the Oligocene, reaching a peak of activity at ca. 30 Ma ago. It is also possible, on geochemical grounds, that there have

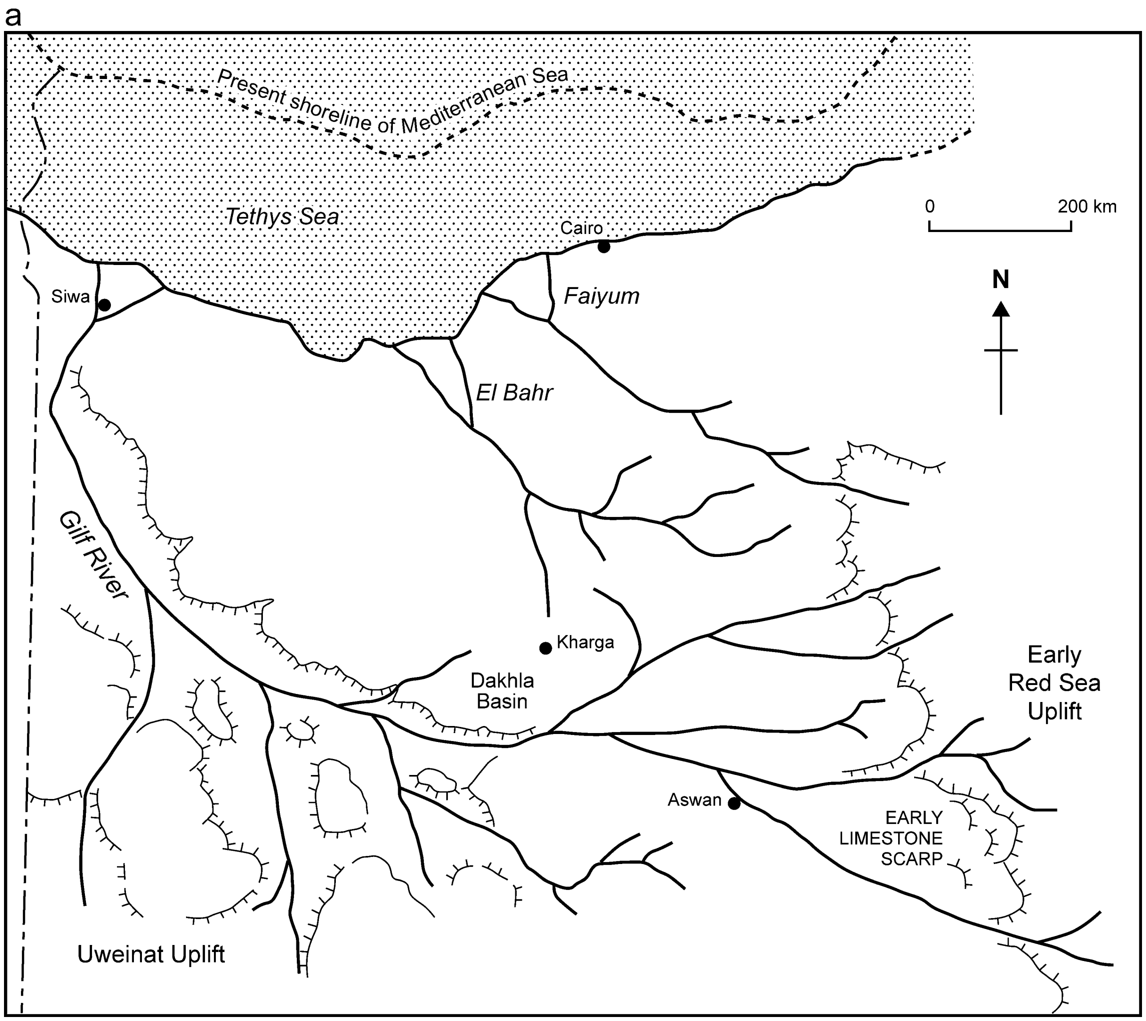

Fig. 4. (a) Sketch showing Gilf system (System I) at approximate end of Oligocene Epoch (Chattian Age, =24 Ma) (modified from Issawi and McCauley, 1992). (b) Sketch showing Qena system (System II) in approximately middle Miocene time (Langian Age, about 16 Ma) (modified from Issawi and McCauley, 1992). (c) Sketch showing Nile system (System III), which resulted from a major drop in sea-level of Mediterranean in Messinian time (about 6 Ma) (modified from Issawi and McCauley, 1992).

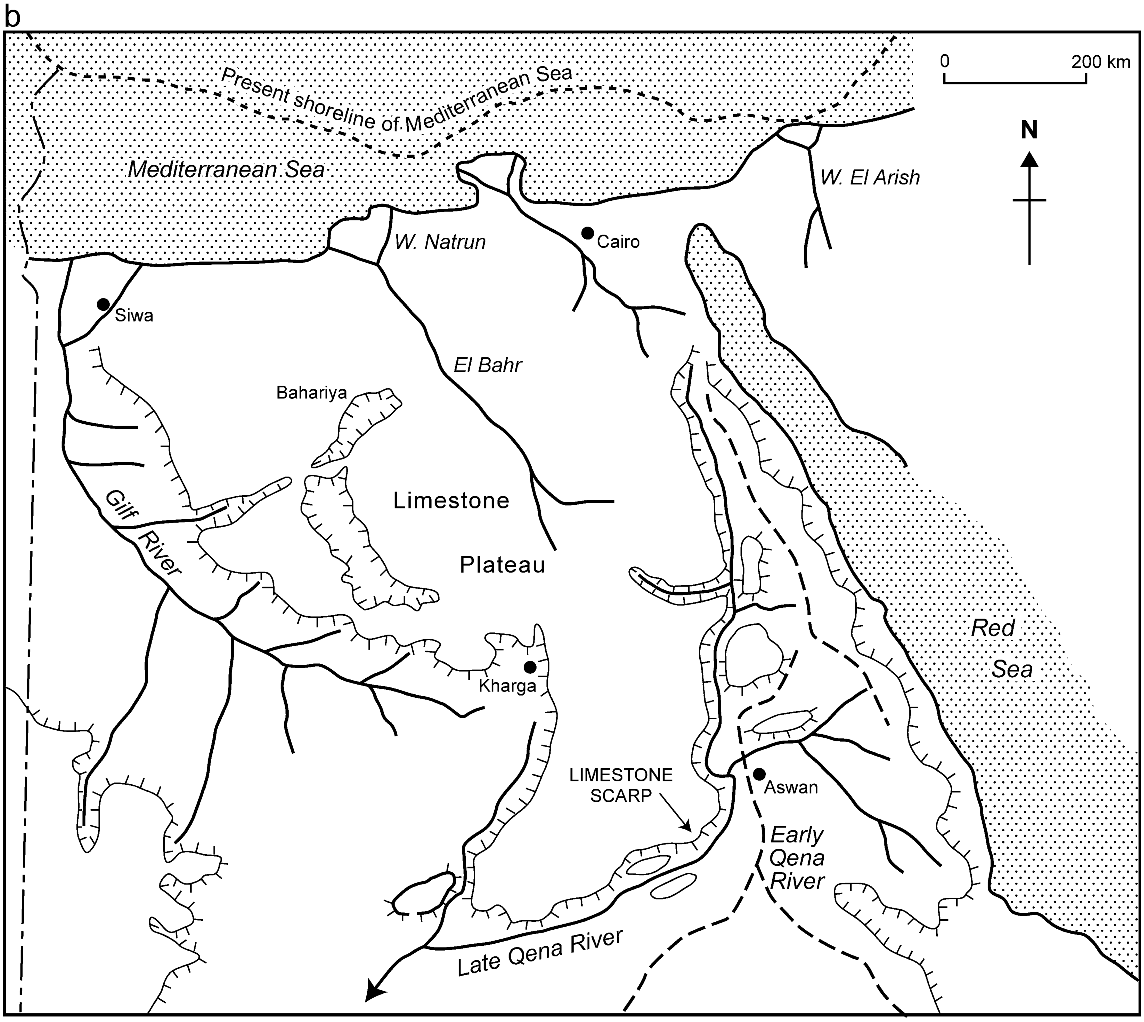

Fig. 4 (*continued*).

been two plumes in East Africa, rather than one. Rogers et al. (2000) have proposed that there was also a Kenyan plume. On the other hand, Ebinger and Sleep (1998) believed that Cenozoic magmatism throughout East Africa could be the result of a single plume.

In the Sudan, the Nile traverses the Sudd, which in the Tertiary may have been a series of lake basins (Salama, 1987), though whether such a lake existed and how big it was is a matter of dispute (see Berry and Whiteman, 1968).

The extent and catchments of the Central African lakes which are related to the Nile system have varied greatly according to rifting, tilting and climatic changes. The present activity of the East African Rift System started ca. 30 Ma ago (Burke, 1996) and by 25 Ma ago was active over a length of about 4000 km stretching from the Gulf of Suez to the Mozambique Channel. Subsidence and lake development has taken place since that time. The Lake Malawi Basin, for instance, has been actively subsiding since the late Miocene (ca. 8.6 Ma) (Contreras et al., 2000).

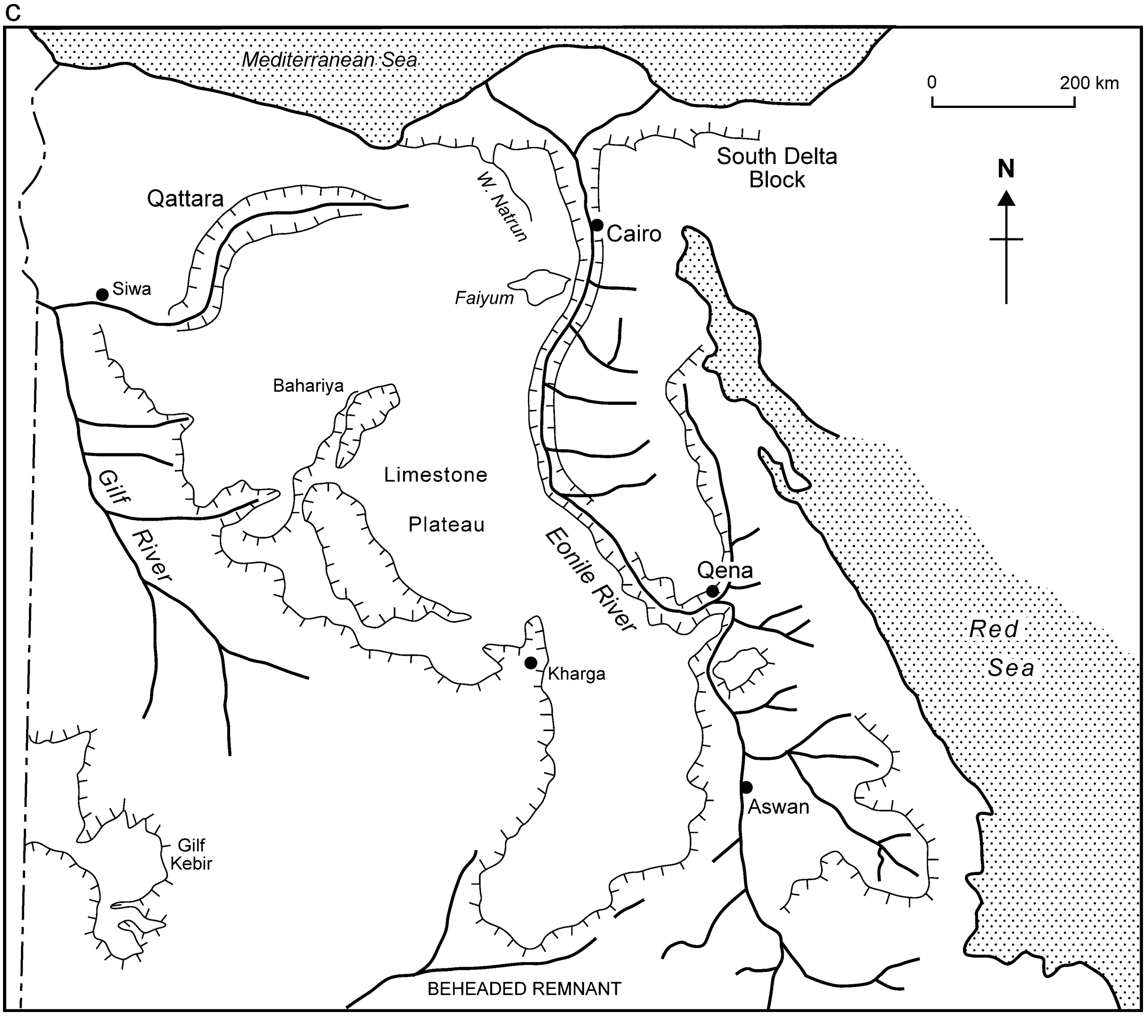

Fig. 4 (*continued*).

Neotectonic activity is still intense and associated faulting has had a major influence on river courses (Vétel et al., 2004). Prior to the formation of the Gregory Rift, about 15 Ma, East Africa seems to have been dominated by a north–south trending arch of crystalline rocks, which formed the continental watershed, with rivers draining east to the Indian Ocean and west towards the Atlantic across the line of the present Western Rift valley (Grove, 1983).

Lake Victoria, seems to be the result of regional tilting and may only be 400,000 years old (Johnson et al., 2000), and this also accounts for the form of Lake Kyoga, the drainage reversal with which it is associated (Fig. 5) (Doornkamp and Temple, 1966) and for Pleistocene drainage evolution in the area between Lake Victoria and Lake Edward in southern Uganda. During Pleistocene dry phases some of the lakes became closed saline systems and did not overflow into the Nile. Lake Victoria only became directly reconnected to the Nile system at ca. 13 ka (Beuning et al., 2002). Conversely some lakes currently cut off from the Nile (e.g. Chew Bahir and

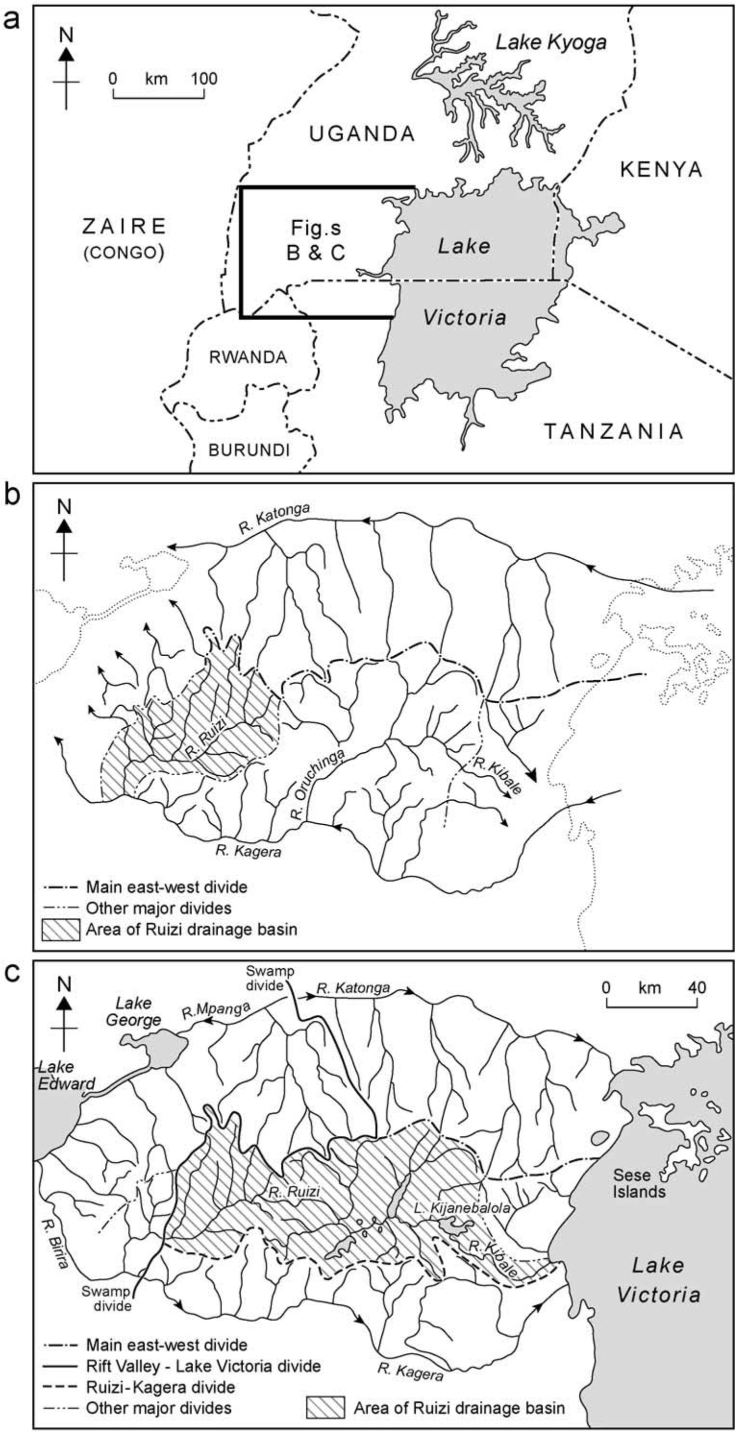

Fig. 5. Changes in drainage pattern to the north and west of Lake Victoria. (a) The location of Lake Kyoga back tilted and flooded drainage. (b) Major drainage lines before middle Pleistocene reversal (modified after Doornkamp and Temple, 1966). (c) Present drainage pattern.

Turkana) overflowed into it during wetter phases via the Sobat. Further south, Lake Rukwa has in the past overflowed into Lake Tanganyika as a result of tiling and Holocene climatic changes (Delvaux et al., 1998).

The date at which the complex sub-basins of the Nile were linked up is the matter of ongoing debate. Butzer and Hansen (1968, pp. 5–6) argued that as late as mid-Tertiary times, prior to the major faulting that produced the rift valleys of East Africa, the present Nile basin was five or more separate hydrographic units.

Williams and Williams (1980, p. 221) suggested that 'the first definitive evidence of Nile flow from Ethiopia through Sudan to Egypt and the Mediterranean is so far only of Lower Quaternary age', whereas Adamson et al. (1993, p. 83) considered that 'the Nile northwards from Ethiopia and from central to southern Sudan dates from at least sometime in the Miocene'. On the other hand, Berry and Whiteman (1968) rejected the idea that the Nile is a very young river and were of the opinion (p. 1) that:

> . . .sections of the Nile system are very old and had their origin in Late Cretaceous times or even earlier. The date of connection is recent in the case of the Bahr el Jebel and the Albert-Victoria sections, but in the central and northern Sudan there must have been a Nile valley in Late Cretaceous and Early Tertiary times. Also in Ethiopia there must have been Miocene and Pliocene Blue Nile systems.

5. The Zaire River

The Zaire (Congo) occupies a large basin in central Africa, a basin which has a narrow exit to the sea (Fig. 6). It has an area of 3.7 million km^2, a length of ca. 4100 km and an annual discharge of ca. 1400 billion m^3 per year. Its tributaries create a branching, leaf-like pattern that is unique in Africa. Most of the major tributaries are oriented towards a point in the centre of the basin rather than towards its outlet (Summerfield, 1991, p. 425). It is also notable for the falls that cross its course between Kinshasha and the sea and for the fact that it has no delta.

It seems possible that in the Tertiary (in the Pliocene according to Beadle, 1974, p. 131) the basin was occupied by a large water body (Peters and O'Brien, 2001) of which lakes Tumba and Maindombe are remnants. This internal drainage may have been captured by a short stream draining to the coast and cutting through the high ground at the continental margin on the western rim of the basin. The point of capture was possibly just below Stanley Pool between Brazzaville and Kinshasha. Burke (1996) has suggested that this may have happened in the last 30 Ma. Terrigenous sediment supply to the West African margin increased dramatically in the Miocene (Lavier et al., 2001) and it is conceivable that this is when the Congo System was firmly linked to the Atlantic. In any event, doming associated with rifting in East Africa in the Miocene would have augmented its flow (Uenzelmann-Nebel, 1998). During the upper Cretaceous, the Ogooe and Kwanza fans had been the most important loci of sedimentation along the West Africa margin, as was the Kouilou/Niari river (Uenzelmann-Nebel, 1998). Lucazeau et al. (2003; Leturmy et al., 2003) surmise that the switch of depocentres and the capturing of the endoreic Congo system may be associated with the flexural uplift created by sediment loading on the Continental Shelf.

6. The Cunene and Coroca

The Cunene rises in the Bié highlands of Angola (Fig. 7) and flows into the Atlantic on the border between Angola and Namibia. For much of its course, it flows southwards, as if towards the Etosha Pan, an ancient structural basin (Buch and Trippner, 1997), but then it turns sharply westwards and enters a tract with steep falls and rapids (e.g. the Caxambue rapids and Ruacana Falls). This seems to be the case of a river capture by a stream eroding backwards from the coast and capturing the interior drainage (Wellington, 1955, p. 65). Wellington also suggests that the conditions for a similar process of capture are present in the headwaters of the Rio Coroca to the north of the lower Cunene. This river, having eroded headward through the Sierra de Chela of the Great Escarpment, is threatening to behead the upper Caculuvar River, a tributary of the upper Cunene. The timing of the Cunene capture is not well constrained (Moore and Blenkinsop, 2002) but lowering of the base-level associated with the opening of

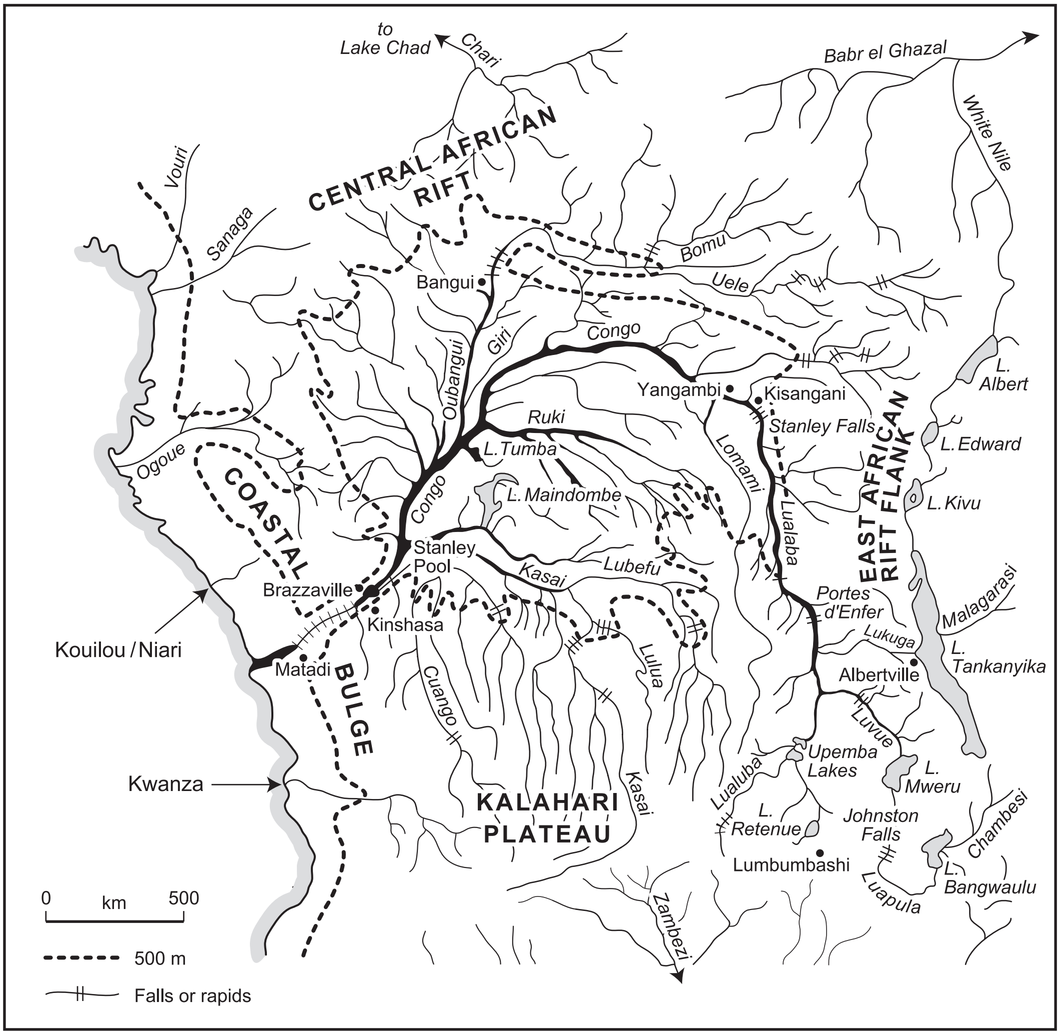

Fig. 6. The Congo (Zaire) Basin. The 500-m contour emphasizes the approximate boundaries of the relatively flat central basin, which may have formerly contained a large lake or lakes.

the Atlantic may have initiated a period of rapid erosion, which may have exploited a Perma–Carboniferous glacial valley from which Karoo sediments were stripped (Martin, 1950). It has also been argued that the capture, which perhaps caused the shrinkage of a postulated large Lake Etosha, occurred only ca. 35,000 years ago (Buch, 1997). At the far western end of its course, as it passes through the coastal sand sea, there are signs that the Cunene formerly entered the sea considerably to the south of its present mouth (Sander, 2002) and that it may have been forced northwards by dune encroachment.

7. The Zambezi

Relatively abrupt changes in the direction and characteristics of its modern course suggests that the Zambezi (which covers an area of ca. 1.33 million km^2) may only relatively recently have become a joined up system. The upper and middle Zambezi are thought to have evolved as separate systems, with the upper Zambezi previously joined to the Limpopo system and the middle Zambezi to the Shire system. It has been argued that the upper Zambezi was captured because of down-warping and tectonic

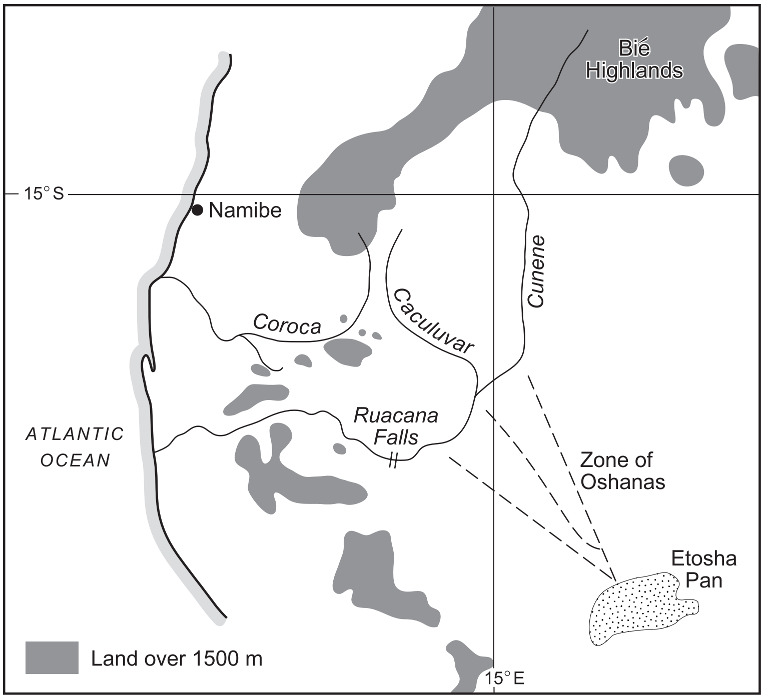

Fig. 7. The Cunene and Coroca rivers.

enhancement of the stream power of the Palaeo–middle Zambezi (Shaw and Thomas, 1988, 1992). This linking of the two systems may have been as recent as the Pliocene or mid-Pleistocene (Thomas and Shaw, 1991, p. 34). The proposed nature of the drainage shifts involving the Zambezi, Kafue, Luangwa and Shire are shown in Fig. 8. After the establishment of the present Zambezi course, enhanced downwarping along the Gwembe trough caused rejuvenation resulting in the rapid development of the Victoria Falls and the formation of the incised middle Zambezi gorge.

8. The Orange River

The Orange River, with a catchment area of 953,200 km^2, is the largest basin in southern Africa. It has shown considerable changes in its pattern and extent since the Cretaceous (Dollar, 1998), and these have been the subject of considerable recent research because old river courses may be sources of diamonds (Moore and Moore, 2004; Jacob et al., 1999).

During the Oligocene, offshore sediment studies indicate that the upper Orange–Vaal system entered the South Atlantic through the Cape Canyon, some 300–500 km south of its present mouth at Orangemund. Subsequently, towards the end of the Miocene, river capture by the Koa River and its tributary headwaters resulted in the diversion of the upper Orange to its present course. The Koa Valley contained a north-flowing perennial system during the middle Miocene. Even later, further tectonic activity and aridification (De Wit, 1999) caused abandonment of the flow through the Koa (Dingle and Hendey, 1984). The Orange may also have drained a large area of the Kalahari, being fed by the Trans-Tswana river of McCarthy (1983). The Molopo, Morokweng and Harts were major north bank tributaries (Bootsman, 1997; Bootsman et al., 1999). Tectonism along the Griqualand–Transvaal Axis and the associated development of the Kalahari basin caused the demise of these important palaeotributaries (Moore, 1999). Just how extensive the Trans-Tswana river was, however, is a matter of contention (Fig. 9), for although McCarthy (1983)

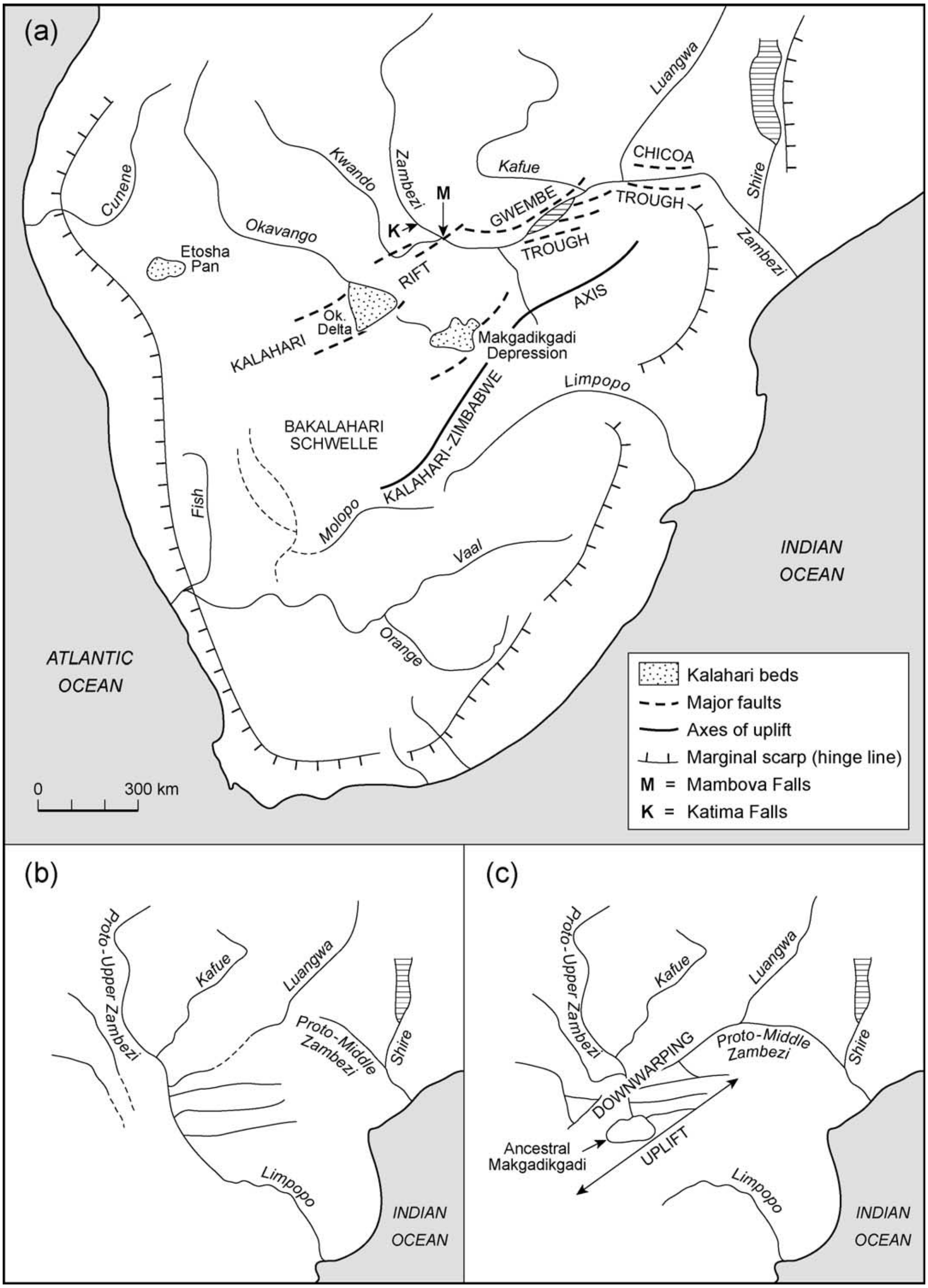

Fig. 8. Drainage development in southern Africa. (a) Major modern drainage lines. (b) The drainage system postdating the division of Gondwanaland. (c) The situation prior to the union of the middle and upper Zambezi in the early Pleistocene (modified after Thomas and Shaw, 1991, Fig. 2.8).

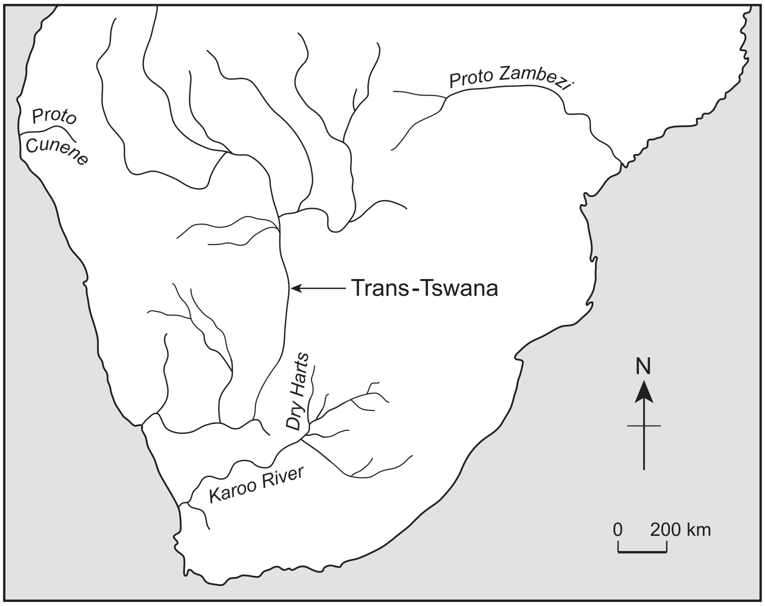

Fig. 9. The hypothetical Trans-Tswana drainage (modified from Dardis et al., 1988, Fig. 2.8).

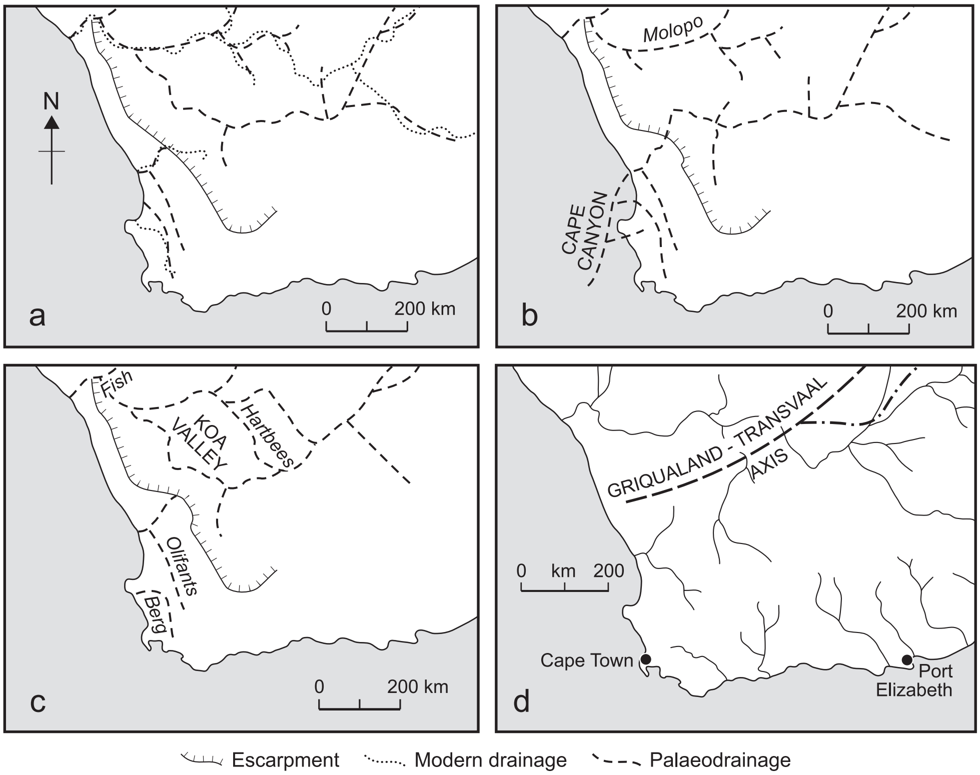

Fig. 10. Reconstruction of the palaeodrainage of the Orange River drainage system. (a) Late Cretaceous, (b) Palaeogene, (c) Neogene (modified after Dingle and Hendey, 1984).

suggested that the catchment area may have extended into tropical Central Africa, and taken in the Kafue, upper Zambezi and possibly the Kwando and Okavango, De Wit et al. (2000) suggest that at least part of that area was drained by the palaeo-Limpopo River.

De Wit (1999) has argued that during the late to middle Cretaceous there were two main rivers draining the interior of Southern Africa. The southern one, termed the Karoo River, had its source in the present Orange/Vaal basin, but had its outlet at the present Olifants River mouth, a finding supported by biogeographical studies (Barber-James, 2003). The northerly one, termed the Kalahari River, drained southern Botswana and Namibia and entered the Atlantic via the lower Orange River (Fig. 10). By the early Cenozoic, however, the lower Kalahari River had captured the upper part of the Karoo River. This he attributed to accelerated uplift of the southern and eastern subcontinental margins at around 100–80 million years ago. The position of the Atlantic outlet of the Kalahari River is disputed, however, and Stevenson and McMillan (2004) suggest that in the Latest Cretaceous the dominant exit was situated offshore the present-day Groen to Buffels rivers.

In Southern Africa, it is possible that the drainage pattern was affected by doming over large mantle plumes (radii of ca. 1000 km) that succeeded continental breakup in the Cretaceous. In the west there was the so-called Paraná plume and in the east the earlier so-called Karoo plume (Moore and Blenkinsop, 2002). At least in some areas, drainage radiated away from the centre of the plumes (Cox, 1989) (Fig. 11), but the precise location and number of the plumes is the matter of debate. Some flank drainages that developed on the Paraná plume could include the Fish and Molopo rivers, the Okavango, Cuango and upper Zambezi and Congo headwaters. This could also explain the striking absence of major westward draining systems between the modern Orange and the Congo.

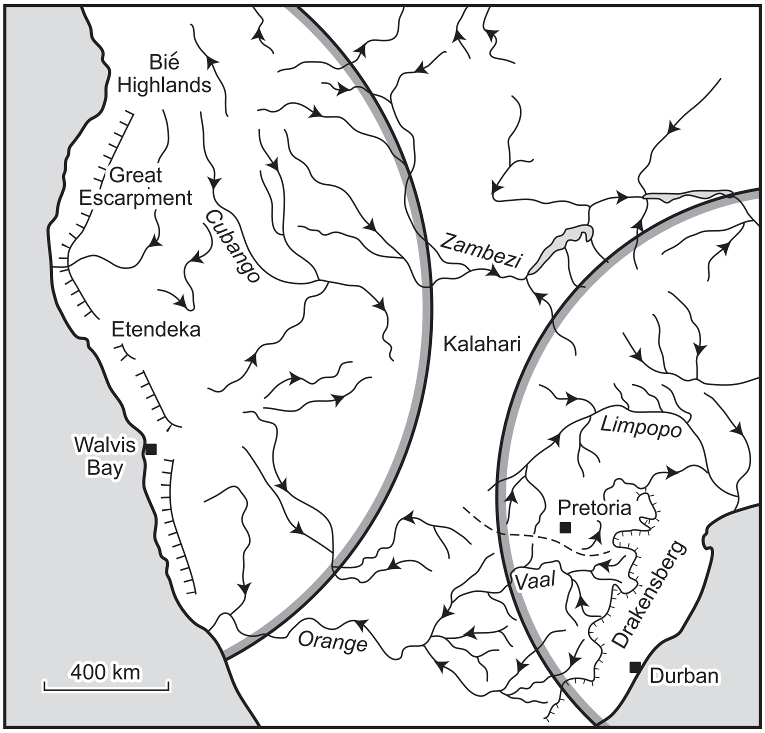

Fig. 11. Postulated locations of major domes associated with Karoo and Paraná mantle plumes and associated drainage patterns (modified after Cox, 1989).

In addition, as elsewhere in Africa (e.g. the Congo, Sudd and Chad basins), interior basins subsided to accommodate sedimentary material in the Cenozoic and these were bounded by uplifting sub-swells such as the Transvaal–Griqualand axis and the Okavango–Kalahari–Zimbabwe axis (Moore and Larkin, 2001). Uplift of these sub-swells contributed to drainage dismemberment (Gumbricht et al., 2001; Partridge and Maud, 1987) and, for example, severed the links between the Limpopo and the Okavango, Cuando and Zambezi-Luangwa system (Moore and Larkin, 2001). The Great Escarpment on the Atlantic coast was also affected by flexural isostatic uplift, with denudation contributing to rift-margin upwarping (Gilchrist and Summerfield, 1990).

In the heart of the Kalahari sandveld, there are a number of defunct drainage systems, *mekgacha*, which appear to have been active during Quaternary pluvials but which are now unable to flow (Shaw et al., 1992).

9. Dune aligned drainage

Recent analysis of remotely sensed imagery has revealed the widespread existence of aligned drainage systems associated with past aeolian activity and dune development across much of Africa. The former expansion of the Sahara southwards towards the Gulf of Guinea and of the Kalahari northwards towards the Congo Basin mean that major dune fields developed which guided the pattern of river courses in subsequent more humid phase. Aligned drainage of this type has been described from southern Angola (Shaw and Goudie, 2002), the Democratic Republic of Congo (de Dapper, 1988), and in southern Nigeria and Cameroon (Nichol, 1998, 1999). There is also an extensive area of aligned drainage with karstic development in the Weissrand Plateau area of southeastern Namibia. It is developed on a Tertiary calcrete surface from which the dunes are now largely absent.

10. Conclusions

In common with Australia (Beard, 2003) and South America (Potter, 1997), it is clear that since the break up of Gondwanaland, the drainage systems of Africa have shown substantial changes. Prior to rifting, drainage may have developed from mantle plumes. After that, there was uplift of the bounding mountains (e.g. the Great Escarpment of southern Africa), subsidence of internal basins (e.g. the Kalahari) and uplift of subswells produced by local mantle upwelling (Burke, 1996). Aggressive rivers, adapting to a new low base level, cut back from the coast and a suite of river captures occurred (e.g. the Cunene and the Congo). In eastern Africa, the growth of the Afar plume, the building of the Ethiopian Plateau and the Red Sea Hills, and the development of the rift valleys caused further fundamental changes in river catchments. In North Africa, the retreat of the Tethys Ocean and the Miocene desiccation of the Mediterranean (with its associated low base level) had a major impact on the Nile and other systems (Griffin, 2002). Accentuated aridification in the Pleistocene caused dune fields to expand and lake basins to shrink and close, created areas of aligned drainage (as in South Angola), blocked and diverted drainage (e.g. the Niger), and isolated lakes from major river systems (e.g. Lakes Victoria and Rukwa).

References

Adamson, D.A., Gasse, F., Street, F.A., Williams, M.A.J., 1980. Late Quaternary history of the Nile. Nature 287, 50–55.

Adamson, D., McEvedy, R., Williams, M.A.J., 1993. Tectonic inheritance in the Nile basin and adjacent areas. Isr. J. Earth-Sci. 41, 75–85.

Barber-James, H.M., 2003. The biogeography of the Prosopistomatidae with a particular emphasis on southern African species. In: Gaino, E. (Ed.), Research Update on Ephemeroptera and Plecoptera. University of Perugia, Perugia, pp. 263–270.

Beadle, L.C., 1974. The Inland Waters of Tropical Africa. Longman, London.

Beard, J.S., 2003. Paleodrainage and the geomorphic evolution of passive margins in southwestern Australia. Z. Geomorphol. 47, 273–288.

Berry, L., Whiteman, A.J., 1968. The Nile in the Sudan. Geogr. J. 134, 1–33.

Beuning, K.R.M., Kelts, K., Russell, J., Wolfe, B.B., 2002. Reassessment of Lake Victoria–Upper Nile River paleohydrology from oxygen isotope records of lake sediment cellulose. Geology 30, 559–562.

Bootsman, C.S., 1997. Indicators of the evolution of the upper Molopo drainage. S. Afr. Geogr. J. 79, 83–92.

Bootsman, C.S., Reimold, W.V., Brandt, D., 1999. Evolution of the Molopo drainage and its possible disruption by the Morokweng impact event at the Jurassic–Cretaceous boundary. J. Afr. Earth Sci. 29, 668–678.

Brookes, I.A., 2001. Possible Miocene catastrophic flooding in Egypt's western desert. J. Afr. Earth Sci. 32, 325–333.

Buch, M.W., 1997. Etosha pan—the third largest lake in the world? Madoqua 20, 49–64.

Buch, M.W., Trippner, C., 1997. Overview of the geological and geomorphological evolution of the Etosha region, northern Namibia. Madoqua 20, 65–74.

Burke, K., 1996. The African plate. S. Afr. J. Geol. 99, 341–409.

Burke, K., Wells, G.L., 1989. Trans-African drainage system of the Sahara: was it the Nile? Geology 17, 743–747.

Butzer, K.W., Hansen, C.L., 1968. Desert and River in Nubia. University of Wisconsin Press, Madison.

Contreras, J., Anders, M.H., Scholz, C.H., 2000. Growth of a normal fault system: observations from the Lake Malawi basin of the East African rift. J. Struct. Geol. 22, 159–168.

Cox, K.G., 1989. The role of mantle plumes in the development of continental drainage patterns. Nature 242, 873–877.

Dardis, G.F., Beckedahl, H.R., Stone, A.W., 1988. Fluvial systems. In: Moon, B.P., Dardis, G.F. (Eds.), The Geomorphology of Southern Africa. Southern Book Publishers, Johannesburg, pp. 30–56.

de Dapper, M., 1988. Geomorphology of the sand-covered plateaux in southern Shaba, Zaire. In: Dardis, G.F., Moon, B.P. (Eds.), Geomorphological Studies in Southern Africa. Balkema, Rotterdam, pp. 115–135.

Delvaux, D., Kervyn, F., Vittori, E., Kajara, R.S.A., Kilembe, E., 1998. Late quaternary tectonic activity and lake level change in the Rukwa Rift Basin. J. Afr. Earth Sci. 26, 397–421.

De Wit, M.C.J., 1999. Post-Gondwana drainage and the development of diamond placers in western south Africa. Econ. Geol. 94, 721–740.

De Wit, M.J.C., Marshall, T.R., Partridge, T.C., 2000. Fluvial deposits and drainage evolution. In: Partridge, T.C., Maud, R.R. (Eds.), The Cenozoic of Southern Africa. Oxford University Press, New York, pp. 55–72.

Dingle, R.V., Hendey, Q.B., 1984. Mesozoic and Tertiary sediment supply to the western Cape Basin and paleodrainage systems in south-western Africa. Mar. Geol. 56, 13–26.

Dollar, E.S.J., 1998. Palaeofluvial geomorphology in southern Africa: a review. Prog. Phys. Geogr. 22, 325–349.

Doornkamp, J.C., Temple, P.H., 1966. Surface, drainage and tectonic instability in part of southern Uganda. Geogr. J. 132, 238–252.

Doucouré, C.M., de Wit, M.J., 2003. Old inherited origin for the present near-bimodal topography of Africa. J. Afr. Earth Sci. 36, 371–388.

Falconer, J.D., 1911. The Geology and Geography of Northern Nigeria. Macmillan, London.

Ebinger, C.J., Sleep, N.H., 1998. Cenozoic magmatism throughout east Africa resulting from impact of a single plume. Nature 395, 788–791.

Gilchrist, A.R., Summerfield, M.A., 1990. Differential denudation and flexural isostasy in formation of rifted-margin upwarps. Nature 346, 739–742.

Goudie, A.S., 2002. Great Warm Deserts of the World: Landscapes and Evolution. Oxford University Press, Oxford.

Griffin, D.L., 2002. Aridity and humidity: north Africa and the Mediterranean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 182, 65–91.

Grove, A.T., 1983. Evolution of the physical geography of the east African Rift Valley Region. In: Sims, R.W., Price, J.H., Whalley, P.E.S. (Eds.), Evolution, Time and Space: the Emergence of the Biosphere. Academic Press, London and New York, pp. 115–155.

Gumbricht, T., McCarthy, T.S., Merry, C.L., 2001. The topography of the Okavango Delta, Botswana, and its tectonic and sedimentological implications. S. Afr. J. Geol. 104, 243–264.

Holmes, A., 1944. Principles of Physical Geology. Thomas Nelson and Sons, Edinburgh.

Issawi, B., McCauley, J.F., 1992. The Cenozoic rivers of Egypt: the Nile problem. In: Adams, B., Friedman, R. (Eds.), The Followers of Horus. Oxbow Press, Oxford, pp. 1–18.

Jacob, R.J., Bluck, B.J., Ward, J.D., 1999. Tertiary-age diamondiferous fluvial deposits of the Lower Orange River Valley, southwestern Africa. Econ. Geol. 94, 749–758.

Jacobberger, P.A., 1981. Geomorphology of the upper inland Niger delta. J. Arid Environ. 13, 95–112.

Johnson, T.C., Kelts, K., Odada, E., 2000. The Holocene history of Lake Victoria. Ambio 29, 2–11.

King, S.D., Ritsema, J., 2000. African hot spot volcanism: small-scale convection in the upper mantle beneath cratons. Science 290, 1137–1140.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999. Chronology, causes and progression of the Messinian salinity crisis. Nature 400, 652–655.

Lavier, L.L., Steckler, M.S., Brigaud, F., 2001. Climatic and tectonic control of the Cenozoic evolution of the west African margin. Mar. Geol. 178, 63–80.

Leturmy, P., Lucazeau, F., Brigaud, F., 2003. Dynamic interactions between the Gulf of Guinea passive margin and the Congo River drainage basin: 1. Morphology and mass balance. J. Geophys. Res. 108 (B8).

Lucazeau, F., Brigaud, F., Leturmy, P., 2003. Dynamic interactions between the Gulf of Guinea passive margin and the Congo River drainage basin: 2. Ioostasy and uplift. J. Geophys. Res. 108 (B8).

Martin, H., 1950. Südwestafrika. Geol. Rundsch. 38, 6–14.

McCarthy, T.S., 1983. Evidence for the former existence of a major, south flowing river in Griqualand west. Trans. - Geol. Soc. South Afr. 86, 37–49.

McCauley, J.F., Schaber, G.G., Breed, C.S., Grolier, M.J., Haynes, C.V., Issawi, B., Elachi, C., Blom, R., 1982. Subsurface valleys and geoarchaeology of the eastern Sahara revealed by shuttle radar. Science 218, 1004–1020.

McIntosh, R.J., 1983. Floodplain geomorphology and human occupation of the upper inland delta of the Niger. Geogr. J. 149, 182–201.

Moore, A., 1999. A reappraisal of epeirogenic flexure axes in southern Africa. S. Afr. J. Geol. 102, 363–376.

Moore, A., Blenkinsop, T., 2002. The role of mantle plumes in the development of continental-scale drainage patterns: the southern African example revisited. S. Afr. J. Geol. 105, 353–360.

Moore, A., Larkin, P.A., 2001. Drainage evolution in south-central Africa since the break up of Gondwana. S. Afr. J. Geol. 104, 47–68.

Moore, J.M., Moore, A.E., 2004. The roles of primary kimberlitic and secondary Dwyka glacial sources in the development of alluvial and marine diamond deposits in southern Africa. J. Afr. Earth Sci. 38, 115–134.

Nichol, J.E., 1998. Quaternary climate and landscape development in west Africa: evidence from satellite images. Z. Geomorphol. 42, 229–347.

Nichol, J.E., 1999. Geomorphological evidence and pleistocene refugia in Africa. Geogr. J. 165, 79–89.

Pachur, H.-J., 1993. Palaeodrainage systeme im Sirte-Becken und seiner Umrahmung. Wurzbg. Geogr. Abh. 87, 17–34.

Pachur, H.-J., Kröpelin, S., 1987. Wadi Howar: paleoclimatic evidence from an extinct river system in the southwestern Sahara. Science 237, 298–300.

Partridge, T.C., Maud, R.R., 1987. Geomorphic evolution of southern Africa since the Mesozoic. S. Afr. J. Geol. 90, 179–208.

Passarge, S., 1904. Die Kalahari. D. Reimer, Berlin.

Peters, C.R., O'Brien, E.M., 2001. Palaeo-lake Congo: implications for Africa's late Cenozoic climate—some unanswered questions. Palaeoecol. Afr. 27, 11–18.

Pickford, M., 2000. Crocodiles from the Beglia formation, middle/late Miocene boundary, Tunisia, and their significance for Saharan palaeoclimatology. Ann. Paléontol. 86, 59–67.

Pik, R., Marty, B., Carignan, J., Lavé, J., 2003. Stability of the upper Nile drainage network (Ethiopia) deduced from (U–Th) thermachronometry: implications for uplift and erosion of the Afar plume dome. Earth Planet. Sci. Lett. 215, 73–88.

Potter, P.E., 1997. The Mesozoic and Cenozoic paleodrainage of South America: a natural history. J. South Am. Earth Sci. 10, 331–344.

Robinson, C., El-Baz, F., Ozdogan, M., Ledwith, M., Blanco, D., Oakley, S., Inzana, J., 2000. Use of radar data to delineate paleodrainage flow directions in the Selima Sand Sheet. Photogramm. Eng. Remote Sensing 66, 745–754.

Rogers, N., Macdonald, R., Fitton, J.G., George, R., Smith, M., Barreiro, B., 2000. Two mantle plumes beneath the East African Rift System: Sr, Nd, and Pb isotope evidence from Kenya Rift basalts. Earth Planet. Sci. Lett. 176, 387–400.

Said, R., 1981. The Geological Evolution of the River Nile. Springer Verlag, New York.

Salama, R.B., 1987. The evolution of the River Nile. The buried saline rift lakes in Sudan el Arab Rift, the Sudd buried saline lake. J. Afr. Earth Sci. 6, 899–913.

Sander, H., 2002. Relief- und Regolithgenese im nordöstlichen Kaokoland/Namibia. Doctoral thesis, University of Köln.

Shaw, A., Goudie, A.S., 2002. Geomorphological evidence for the extension of the Mega-Kalahari into south-central Angola. S. Afr. Geogr. J. 84, 182–194.

Shaw, P., Thomas, D.S.G., 1988. Lake Caprivi: a late Quaternary link between the Zambezi and middle Kalahari drainage. Z. Geomorphol. 32, 329–337.

Shaw, P., Thomas, D.S.G., 1992. Geomorphology, sedimentation and tectonics in the Kalahari Rift. Isr. J. Earth-Sci. 41, 87–94.

Shaw, P.A., Thomas, D.S.G., Nash, D.J., 1992. Quaternary fluvial activity in the dry valleys (mekgacha) of the middle and southern Kalahari, southern Africa. J. Quat. Sci. 7, 273–281.

Stevenson, I.R., McMillan, I.K., 2004. Incised valley fill stratigraphy of the upper cretaceous succession, proximal Orange Basin, Atlantic margin of southern Africa. J. Geol. Soc. 161, 185–208.

Summerfield, M.A., 1991. Global Geomorphology. Longman, Harlow.

Summerfield, M.A., 1996. Tectonics, geology and long-term landscape development. In: Adams, W.M., Goudie, A.S., Orme, A.R. (Eds.), The Physical Geography of Africa. Oxford University Press, Oxford, pp. 1–17.

Talbot, M.R., 1980. Environmental responses to climatic change in the west African Sahel over the past 20,000 years. In: Williams, M.A.J., Faure, H. (Eds.), The Sahara and the Nile. Balkema, Rotterdam, pp. 37–62.

Thomas, D.S.G., Shaw, P., 1991. The Kalahari Environment. Cambridge University Press, Cambridge.

Tricart, J., 1965. Rapport de la mission reconnaissance géomorphologique de la vallée moyenne du Niger. Mém. Inst. Fondam. Afr. Noire 72, 193 pp.

Uenzelmann-Nebel, G., 1998. Neogene sedimentation history of the Congo fan. Mar. Pet. Geol. 15, 635–650.

Urvoy, Y., 1942. Les basins du Niger. Mém. Inst. Fondam. Afr. 4, 139 pp.

Vétel, W., Le Gall, B., Johnson, T.C., 2004. Recent tectonics in the Turkana Rift (North Kenya): an integrated approach from drainage network, satellite imagery and reflection seismic analyses. Basin Res. 16, 165–181.

Wellington, J., 1955. Southern Africa: a geographical study. Physical Geography vol. I. Cambridge University Press, Cambridge.

Williams, M.A.J., Adamson, D.A. (Eds.), 1982. A Land Between Two Niles: Quaternary Geology and Biology of the Central Sudan. Balkema, Rotterdam.

Williams, M.A.J., Williams, F.M., 1980. Evolution of the Nile Basin. In: Williams, M.A.J., Faure, H. (Eds.), The Sahara and the Nile. Balkema, Rotterdam, pp. 201–223.