The Present Day Drainage Patterns of the Congo River System and their Neogene Evolution 15

Tyrel J. Flügel, Frank D. Eckardt, and Fenton P.D. Cotterill

"*A river or a drainage basin might best be considered to have a heritage rather than an origin. It is like an organic form, the product of a continuous evolutionary line through time*" *p. 421 Leopold et al. (1964)*

15.1 Introduction

The immense *ca*. 3.67 million km^2 Congo Basin (CB) is an intracontinental basin occupying central Africa. This roughly circular basin stretches across 22° of longitude (from ~12°E to ~34°E) and 21° of latitude (from ~9°N to~13°S) (Figs. 15.1 and 15.2). The basin's unique location straddling the Equator and its size and shape allows the Congo River (CR) to maintain a near constant flow year round: its immense size and exposure to continuous precipitation results in an annual discharge of $1{,}250 \times 10^9$ m^3 (Meade 1996). This discharge makes the CR Africa's largest river and the world's second largest river in terms of volume, only being surpassed by the Amazon with a discharge $6{,}300 \times 10^9$ m^3 (Meade 1996). The CR is the culmination of a complex and extensive drainage network that exhibits localised drainage patterns and controls. As there appears to be no clear correlation between the present day solid loads of the large river systems and the climatic conditions, Pinet and Souriau (1988) consider that relief is the major controlling factor of the development of the drainage systems of the CB. The drainage network of the Congo River System (CRS) suggests a multi-stage and sometimes interlinked development of the basins river systems (Figs. 15.3 and 15.4). As rivers are one of the major drivers of topographic change, a better understanding of their evolution will provide insights into the evolution of the broader landscape of the CB.

The river systems of the CB are described in terms of their present day drainage pattern and fluvial evolution in order to better understand the geomorphic evolution of the basin during the Neogene. Here, the term CB refers to the hydrographic network of the CRS and its associated landscapes. This network incorporates the geologically delimited central Congo Basin and extends eastward to include the Lake Tanganyika and Malagarasi systems (Figs. 15.1, 15.2 and 15.3). Ultimately, the water from the CRS flows into the Atlantic Ocean via the CR mouth near Monanda (Fig. 15.1c). The discharge of the CR is connected to an active deep sea fan by the 1,135 km long, meandering and deeply incised submarine Congo Canyon (Fig. 15.2; Babonneau et al. 2002). The outflow and sedimentary load of the CR comprises of integrated chemical and lithological inputs from runoff across a diverse range of climatic and tectonic terranes of its catchments (Dupré et al. 1996; Lavier et al. 2001). The CR exports a total of 87×10^6 t of matter per a year (Laraque et al. 2009), with a mechanical and chemical erosion rate of 8 t/km^2 yr^{-1} and 5 t/km^2 yr^{-1} respectively, as measured at Pool Malebo (Stanley Pool) (Fig. 15.5; Gaillardet et al. 1995).

The high rainfall associated with the Africa Equatorial region also sustains the world's second large continuous forest covering a *ca*. 2.8 million km^2 area that stretches from ~5°S to ~4°N (Fig. 15.1b). This Equatorial forest supports exceptionally rich biodiversity with the highest species richness in Africa (WWF 2006) and is bisected by the CR. Both the basin's extent and its vast, dense forests have impeded detailed geomorphic investigations. This is especially true of the central basin (*Cuvette Central*) landscapes, and much of the existing data and chronology has been derived from studies closer to the basin's peripheries. The study of the rivers that flow through the

T.J. Flügel (✉) • F.D. Eckardt
Department of Environmental and Geographical Science, Upper Campus, University of Cape Town, Private Bag X3, Rondebosch, Cape Town 7700, South Africa
e-mail: tyrelflugel@gmail.com; frank.eckardt@uct.ac.za

F.P.D. Cotterill
AEON Geoecodynamic Research Hub, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602, Stellenbosch, South Africa
e-mail: fcotterill@gmail.com

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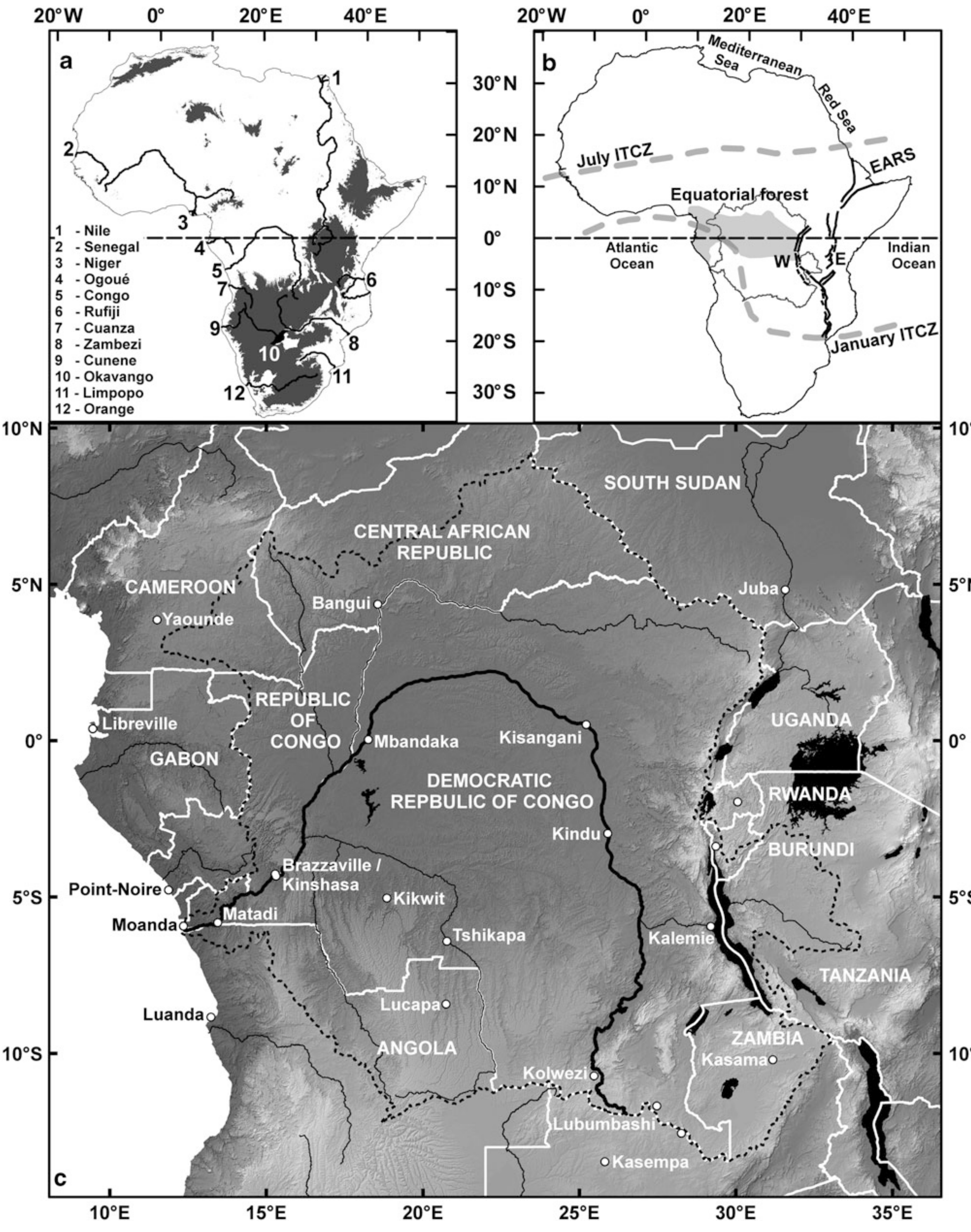

Fig. 15.1 The geographical setting of the Congo River System (CRS). (A) Illustrates the CRS in relation to several other large African rivers (*numbered*). The *grey* shading indicates elevations above 1,000 m.a.s.l., highlighting the biomodal topography of Africa. (B) The extent of the Congo Basin (*dark grey line*) and the Equatorial forest (*light grey* shading) in central Africa. Central Africa is an area of high rainfall, which is related to the movement of the Inter-Tropical Convergence Zone (ITCZ); the maximum extent of which is indicated by the *dashed grey lines*. The East African Rift System (EARS) forms two branches: the Eastern (E) with the Western (W) branch forming part of the eastern boundary of the Congo Basin. (C) The Congo Basin (*dashed black line*) straddles the Equator and measures *ca*. 2,600 km at its longest and *ca*. 2,400 km at its widest. The CB extends beyond the Democratic Republic of Congo into Gabon, Cameroon, Republic of the Congo, Central African Republic, Rwanda, Burundi, Tanzania, Zambia and Angola. Selected town (*white circles*) and countries (*heavy white lines*) are named. Major rivers and waterbodies are shown in solid *black*. Note that the Congo River crosses the Equator twice

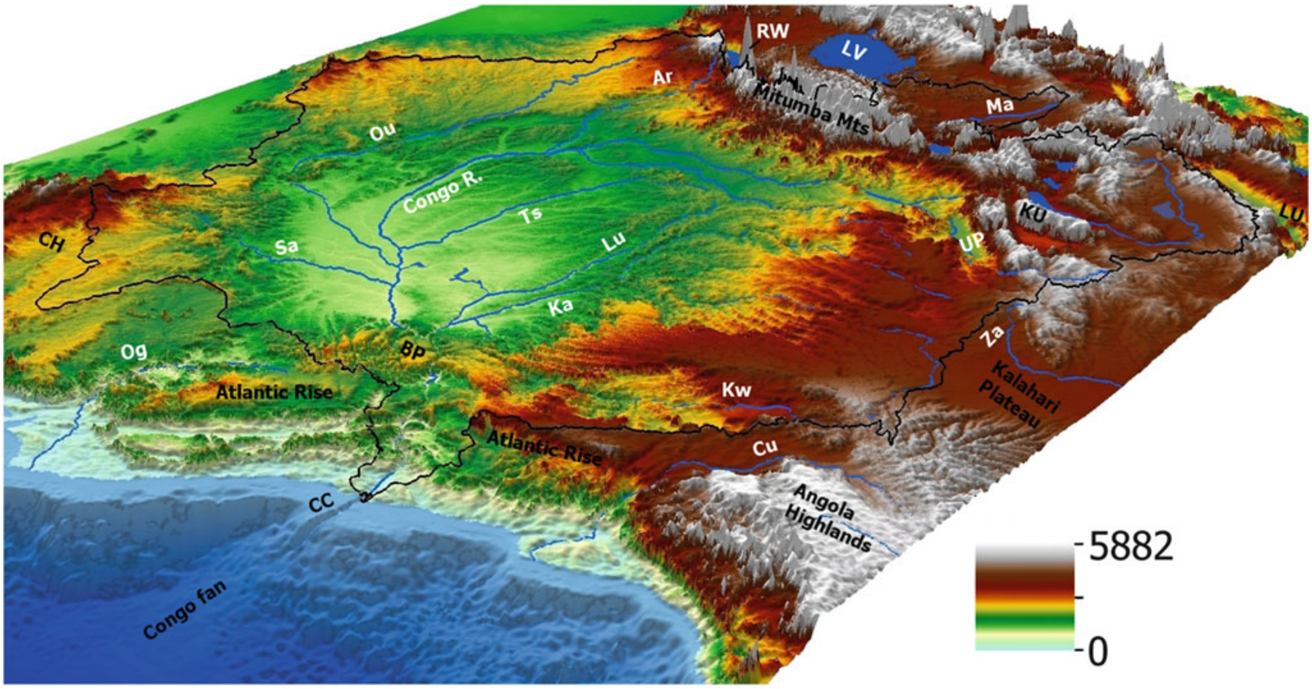

Fig. 15.2 A north-east facing terrain view of central Africa, highlighting major features of the CB. The limit of the hydrographic CB basin is shown (*heavy black line*). Notable rivers are—*Ar* Aruwimi, *Cu* Cuanza, *Ka* Kasai, *Kw* Kwango, *Lu* Lukemie, *Ma* Malagarasi, *Og* Ogoué, *Ou* Oubangui, *Sa* Sangha, *Ts* Tshuapa and Za Zambezi. Major landforms labelled include—CC Congo Canyon, CH Cameroon Highlands, KU Kundelungu Plateau, LU Luangwa Valley, LV Lake Victoria, RW Rwenzori Mountains, UP Upemba trough, BP Batéké Plateau (generated from: ETOPO1 (Amante and Eakins 2009) and SRTM DEM V4 250 m (Reuter et al. 2007; Jarvis et al. 2011)

Equatorial forest, not only the CR and its large tributaries (e.g. Tshuapa) reveal insights into the development of these central basin landscapes. Understanding the interplay between tectonically induced topography and geomorphic responses of fluvial networks can reveal where and when important events occurred in fluvial evolution (Karner and Driscoll 1999; Burbank and Anderson 2001).

Recent advances in remote sensing and availability of digital geospatial datasets makes it feasible to study the CRS in greater detail. In particular the digital surface model (DSM) derived from the Shuttle Radar Topography Mission (SRTM) (Kobrick 2006; Reuter et al. 2007) has enabled the characterisation of the large scale geomorphology of the CB (Figs. 15.2 and 15.3). Utilising this dataset in conjunction with biological evidence (phylogeographic data), we have analysed aspects of the Neogene evolution of the CRS.

15.2 The Congo Basin

15.2.1 Overview

The crescent shaped CR is the only large river in the world to cross the Equator twice (Fig. 15.1), ensuring that some sector of the river always experiences a wet season. The present day climate of the CB is dominantly tropical (hot and humid) around the equatorial region. As the basin straddles the north-south global climatic zone, the seasonal movement of the Inter-Tropical Convergence Zone (ITCZ) is the dominant controlling factor of rainfall in the basin (Fig. 15.1b). The basin thus experiences the northern hemisphere wet season from April to September that maintains the outflow of the southerly flowing tributaries (e.g. the Oubangui River), with northerly flowing tributaries of the southern catchment having high flows during the southern wet season, from October to May. The equatorial basin interior receives 1,600–2,400 mm of rainfall per a year (Nicholson 2000; Runge 2007). A large portion of the northern central and eastern CB north Equator has no dry season, while the rest of the basin experiences two wet and dry season; maximum rainfall occurs over November—December with the rainy season being 7–12 months long (Nicholson 2000). This results in the CR having a double discharge peak flow regime, although there is a limited water level fluctuation in Malebo Pool (Runge 2007). The larger peak occurs during November–January, and a smaller, second peak occurs during April–June (Laraque et al. 2009). The southern highlands (ranging from *ca*. 850 to a maximum of *ca*. 1,400 m.a.s.l) are cooler and drier compared to the central basin, with the highlands (*ca*. 900 m to maximum of *ca*. 3,000 m.a.s.l) in the east being cool and wet. Since the

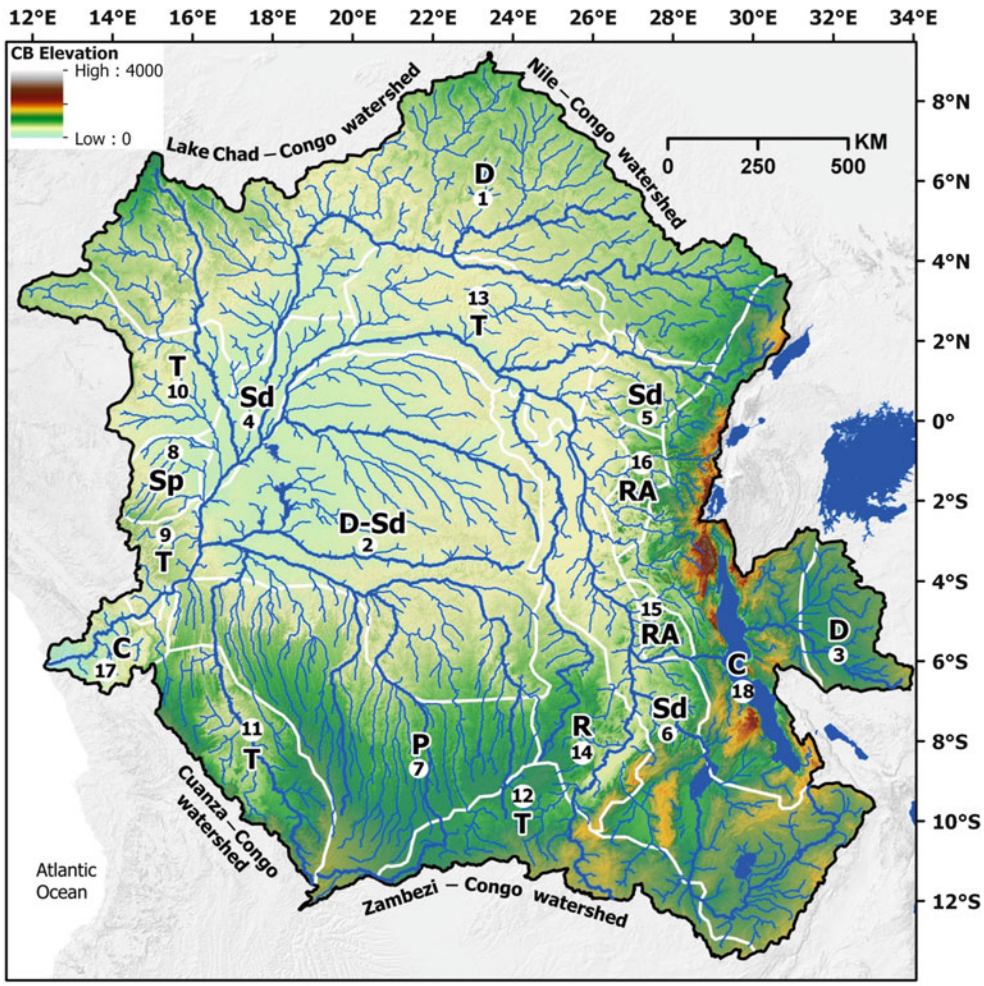

Fig. 15.3 Present day drainage patterns of the CB, elevations and major drainage patterns including *C* contorted, *T* trellis, *D* dendritic, *Sd* sub-dendritic, *P* parallel, *Sp* sub-parallel, *R* rectangular, *RA* rectangular-angulate (*white lines*). Refer to Table 15.1 for pattern descriptions and Table 15.2 for drainage pattern classification. River courses generated from the SRTM DEM V4 250 m (Reuter et al. 2007 and Jarvis et al. 2011)

beginning of the twentieth Century the CR experienced a near constant flow (Laraque et al. 2001). During the 1960s, the CR recorded a discharge exceeding the previous 40 years average, which was followed by a 10 % drop in its interannual discharge in the 1990s which may be related to the high degree of variability of rainfall over central Africa over decadal and centennial time scales (Nicholson 2000; Laraque et al. 2001). Owing to differential denudation between high and low relief of the CB, development in the drainage network will occur different rates throughout the basin (Pinet and Souriau 1988).

The first order geomorphology of the CB can be attributed the interplay between the geodynamics that have led to Africa's bimodal topography (Fig. 15.1a), controls of tectonics (uplift and rifting) and surface processes. The latter have resulted in incision and erosion of valleys around the basin margins, with concomitant deposition of thick lacustrine and fluvial sediments and autogenic river rearrangements, sometimes across drainage divides (Fig. 15.2). For example, during the Palaeogene there was extensive reworking, transport and deposition of sediments within Africa, with limited erosion of the cratonic areas, as evidenced by widely distributed Palaeogene sediments over continental Africa (Seranne et al. 2008). These surface processes, in turn are linked to climatic factors, with past effects of this climatic signal being preserved in the sedimentary record (e.g. Linol et al., this volume, Chap. 11, this Book). The present day CRS preserves evidence of important geomorphic and tectonic events. These events include breaching of pre-existing barriers (pertinently the Atlantic Rise) and expansion of the CRS, especially along its southern margins by drainage capture events. The latter have been most important in significantly increasing the total area of the southern catchment.

Evidence of first order events of the CB's Cenozoic development, including fluvial changes and climatic and geodynamic signals are indicated in the offshore terrigenous sedimentary evidence (Lavier et al. 2001). The Oligocene saw large amounts of sediments transported into the Lower Congo Basin, a consequence of late Cenozoic uplift and formation of the Congo River, forming the Cenozoic Congo deep sea fan (Anka and Séranne 2004; Seranne et al. 2008; Anka et al. 2010; Linol et al., Chap. 10, this book). The Neogene saw an increase of terrigenous sediment deposition in the coastal zone (Lavier et al. 2001) that was likely a result of due to a period of sustained uplift in the Miocene, with sediment supply being further enhanced by a climatic shift (Lavier et al. 2001; Seranne et al. 2008). During the recent past the region was drier during the late Pliocene—Pleistocene and based on sedimentary evidence it is thought that the rivers have remained relatively stable throughout the Quaternary (Guillocheau et al., Chap. 14, this book).

15.2.2 Regional Geomorphological Structure

Since the break-up of Gondwana, Africa's principal drainage systems have undergone substantial rearrangements (Goudie 2005). Details of these rearrangements for the central Africa are poorly known. While much of the Congo Basin's drainage may post-date the break-up of Gondwana, the drainage incorporates many older, inherited structures that have their origins in the assembly of Gondwana. Some of these structures, such as cratons and lithospheric fabrics, continue to maintain a dominant, regional, controlling influence over the geomorphology. This includes consideration of Mesozoic and Cenozoic events, especially where the basin's structural controls persist. However, it appears that events in the Neogene have had the most discernible impacts on the geomorphology of the CB. This is especially true where the eastern Congo Basin has been, and is currently, heavily impacted by the Western branch of the East African Rift System (EARS) and its incipient south-western extension, especially in the Katanga region of south-eastern Democratic Republic of Congo (DRC; Fig. 15.1b, c). Untangling the complex nature of the CRS represented in all the forms and features that comprise the basin, requires an appreciation of their context and interrelationships. Below we summarize the main evidence that allow a synthesis of the Cenozoic evolutionary history of the CB. This evidence comes mainly from the offshore sedimentary record and regional geomorphological structure.

The deep sea Congo Fan, centred on the modern CR outlet, is composed of two units, a Cretaceous and mid- to late-Cenozoic (Oligocene to Present) unit, suggesting two cycles of offshore deposition (Anka et al. 2010). Although the exact palaeo-coastal drainage is unknown, as is the age and nature of the initial canyon, the Congo's outlet has remained fairly stable since Late Cretaceous, although sediment deposition has not been constant (Anka et al. 2010). For example, an early Cenozoic sedimentary hiatus on the Congo Fan was ended by the establishment of a CR-Atlantic Ocean connection during the mid Cenozoic (Anka et al. 2010; see Linol et al., Chap. 10, this book). A steady increase in offshore sediment depositions since the Neogene to the Present suggest an ongoing phase of incision of the Cretaceous–Paleogene sedimentary sequence within the CB and consequent exposure of the cratonic basement (Seranne et al. 2008; Anka et al. 2009). Thus, during the Cenozoic, the CB has undergone a period of reworking followed by a period of increasing incision, a model which fits with the increase of terrigenous sedimentation in the continental passive margin off Gabon-Congo-Angola (equatorial Africa) and the growth of the deep sea fan in the Neogene (Anka and Séranne 2004; Anka et al. 2010). This temporal evolution of erosion-transport-deposition has been correlated with dramatic climatic changes in the Cenozoic that are thought to have resulted in increased mechanical erosion which correlates with increased terrigenous material being transported to the margin observed in the Neogene (Lavier et al. 2001; Seranne et al. 2008).

Presently the CB ranges in elevation, from sea level at the Congo River's outlet near Moanada (downstream of Matadi; Fig. 15.1c), to heights in excess of 3,000 m.a.s.l in the Mitumba Mountains (in the south-east) with the Rwenzori Range, one of Africa's highest mountain ranges (exceeding 5,000 m.a.s.l) lying just outside of the CRS (Fig. 15.2). Overall the Basin has a mean elevation of ~900 m.a.s.l. The *Cuvette Central* and northern areas of the basin are low regions (*ca*. 290–400 m.a.s.l) with subdued relief (Figs. 15.2 and 15.3). They are bounded to the south by dissected watershed, comprised principally of the Angolan Highlands, the northern limit of the Kalahari Plateau in the south and margins of the EARS (Figs. 15.1, 15.2, 15.3 and 15.5). This Western Branch of the EARS runs the entire length (*ca*. 2,100 km) of the eastern margin of the Congo Basin (Fig. 15.1b). This rugged relief consist of a series of elongated, narrow rift valleys and scarps extending from Lake Albert (~3°N) in the north to Lake Malawi (10°S). In the west, Congo basin is bounded by the Atlantic Rise (also known as the Western Escarpment and Monts Crystal), which has been deeply incised by the channel of the lower Congo. The Basin's northern extent is delimited by watersheds shared with the Ogoué River in the west, including parts of the Cameroon Highlands which extends eastward to form the Asande Rise (North Equatorial Plateau) in the north east zone of the CB.

The western and eastern highlands of the Congo Basin, being of tectonic origin (the West Congo Orogen and EARS respectively), exhibit high topographic roughness. The northern watershed incorporates parts of the Central African mobile belt (see de Wit and Linol, Chap. 2 this book). The Basin's highlands are dominated by the plateau, as exemplified by the Congo-Zambezi watershed (Fig. 15.3; Dixey 1943), which corresponds to a change of Africa's bimodal topography, from the low Congo basin (*ca*. 400 m.a.s.l) to the high Kalahari Plateau (*ca*. 1,100 m.a.s.l; Fig. 15.6a–c). The Congo River receive significant inflow in the *Cuvette Centrale* from several large tributary rivers. These systems include the Sanhga and Oubangi from the north and the Kasai (Kasai—Kwango—Lukemie) and

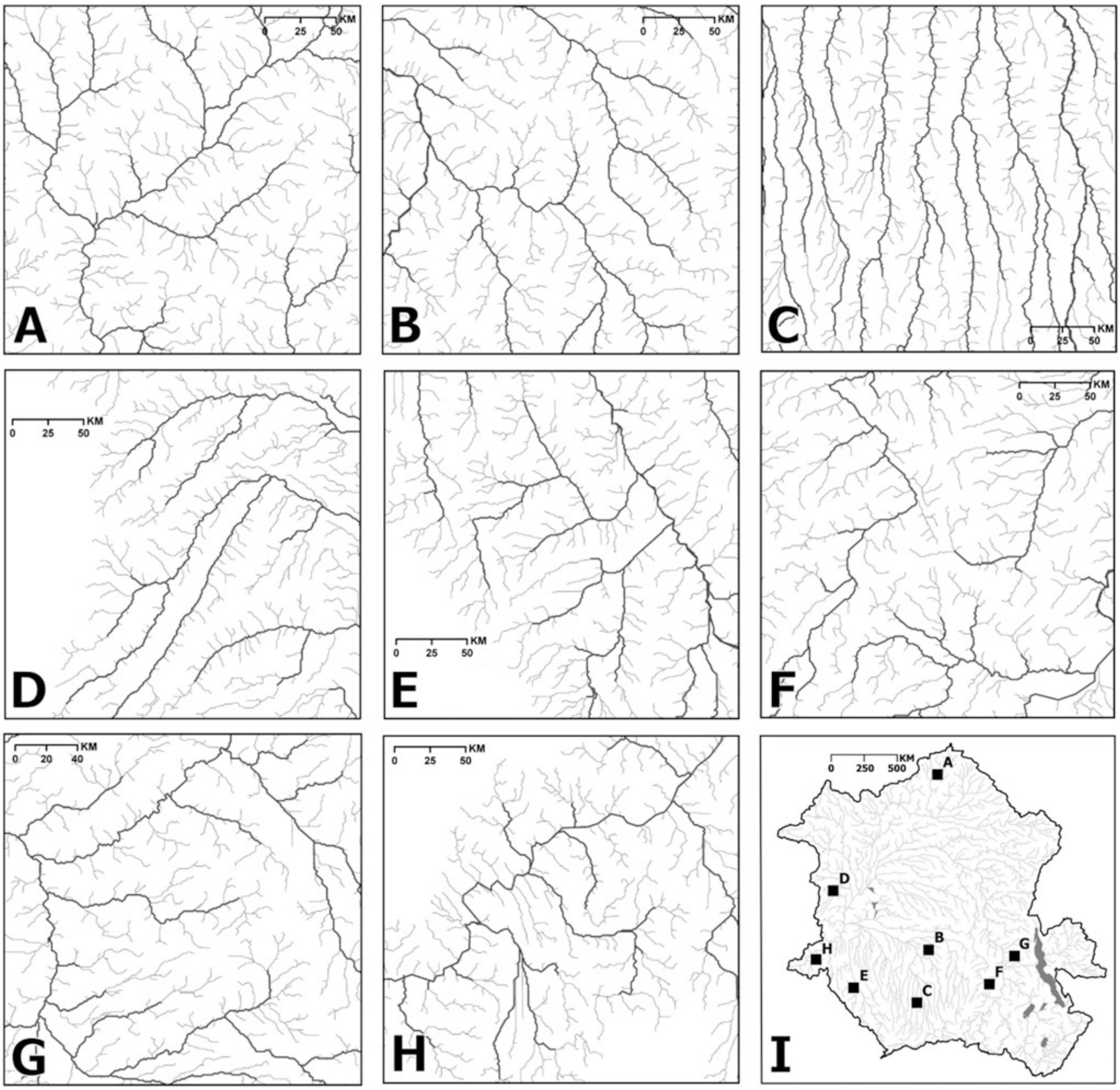

Fig. 15.4 Examples of the drainage types found within the Congo Basin, with stream channels derived from the SRTM data. The corresponding drainage types are : (A) Dendritic, (B) Sub-dendritic, (C) Parallel, (D) Sub-parallel, (E) Trellis, (F) Rectangular, (G) Rectangular-angulate, (H) Contorted. (I) shows the approximate locations of the drainage examples. Refer to Table 15.1 for pattern descriptions and Table 15.2 for drainage pattern classification. Stream channels were generated from SRTM DSM V3 90 m (Reuter et al. 2007; Jarvis et al. 2008)

Lomami and Tshuapa Rivers (Figs. 15.2 and 15.5). Late Neogene and Quaternary alluvium mantling this oval, shallow bowl like depression overlie thick continental sediments (Runge 2007; Guillocheau et al., Chap. 14, this book). These continental sediments are thought to originate from the erosion of the surrounding periphery of the basin and have been accumulating in the basin since the mid Paleozoic (e.g. Linol et al., Chaps. 7 and 11, this book). The subdued surface relief of the *Cuvette Central*, along with thick sedimentary deposits and reworked sediments of the Congo River, has lead several authors to suggest that the central CB has experienced a tendency for recurrent subsidence, with corresponding uplift around its edges (Linol et al., Chap. 11, this book).

The southern reaches of the Congo Basin are dominated by the northward extension of the Kalahari Plateau (Figs. 15.2 and 15.5). It is along this plateau that the watershed of the northward flowing Congo rivers and the

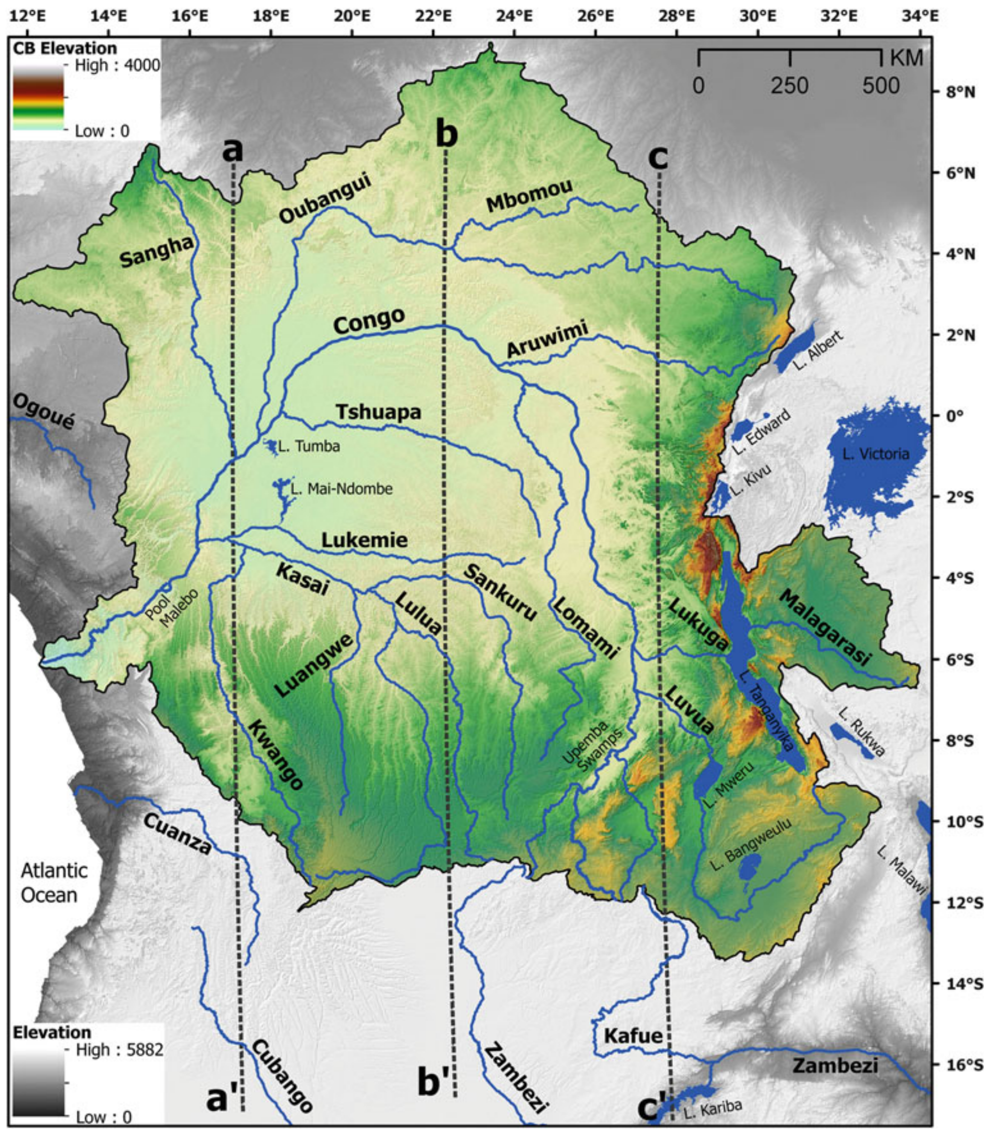

Fig. 15.5 The topography of CB system depicting major rivers and water bodies of the region. The placement of the topographic north-south cross-sections (a, b and c) as seen in Fig. 15.6a, b and c are shown

southward flowing rivers of the Okavango-Zambezi is found as well as that of the coastal draining Cuanza system (Figs. 15.2 and 15.5). In the west this plateau region consists of the dome like Angolan Highlands and its surrounds, further east: including the Bulozi plains and the Kafue Highlands (Moore et al. 2007, Figs. 15.5 and 15.6a). The western region is heavily eroded by the Cuanza River and the Kwango River in the west, with the Kwango River having eroded to the Precambrian basement in parts of its deep valley (Figs. 15.5 and 15.6a). A shallow basin formed by the Sangha, Oubangi and Congo rivers in the north of Fig. 15.6a represents the site of Western Congolian wetland complex. Moving eastward (Fig. 15.6b) one can see that the transition from the southern highland regions to the basin is the most gentle in this zone, relative to the western and eastern sections (Fig. 15.6a, c).

The topographic enhancement contributed by the EARS is illustrated in the rough topography of cross-section C (Fig. 15.6c). The area around the EARS is dominated by rectangular and modified drainage. Several phases of tectonics, rifting and uplift associated with the EARS has resulted in several steep, incised valleys flowing west, directly into the basin (Bauer et al. 2010; Ring 2008; Roller et al. 2010). The relief of the southern portion of the eastern catchments are dominated by the Kundelungu Plateau which has been uplifted to an elevation higher than that of the Congo-Zambezi watershed (Figs. 15.2 and 15.6c). Thus, the mean elevations of these southern Congo tributaries range from 1,000–1,400 m.a.s.l, compared to the elevations of 550–900 m.a.s.l of the northern tributaries (Figs. 15.5 and 15.6c). Of interest is the higher mean elevation of the eastern section of the southern basin (the Chambeshi River region)

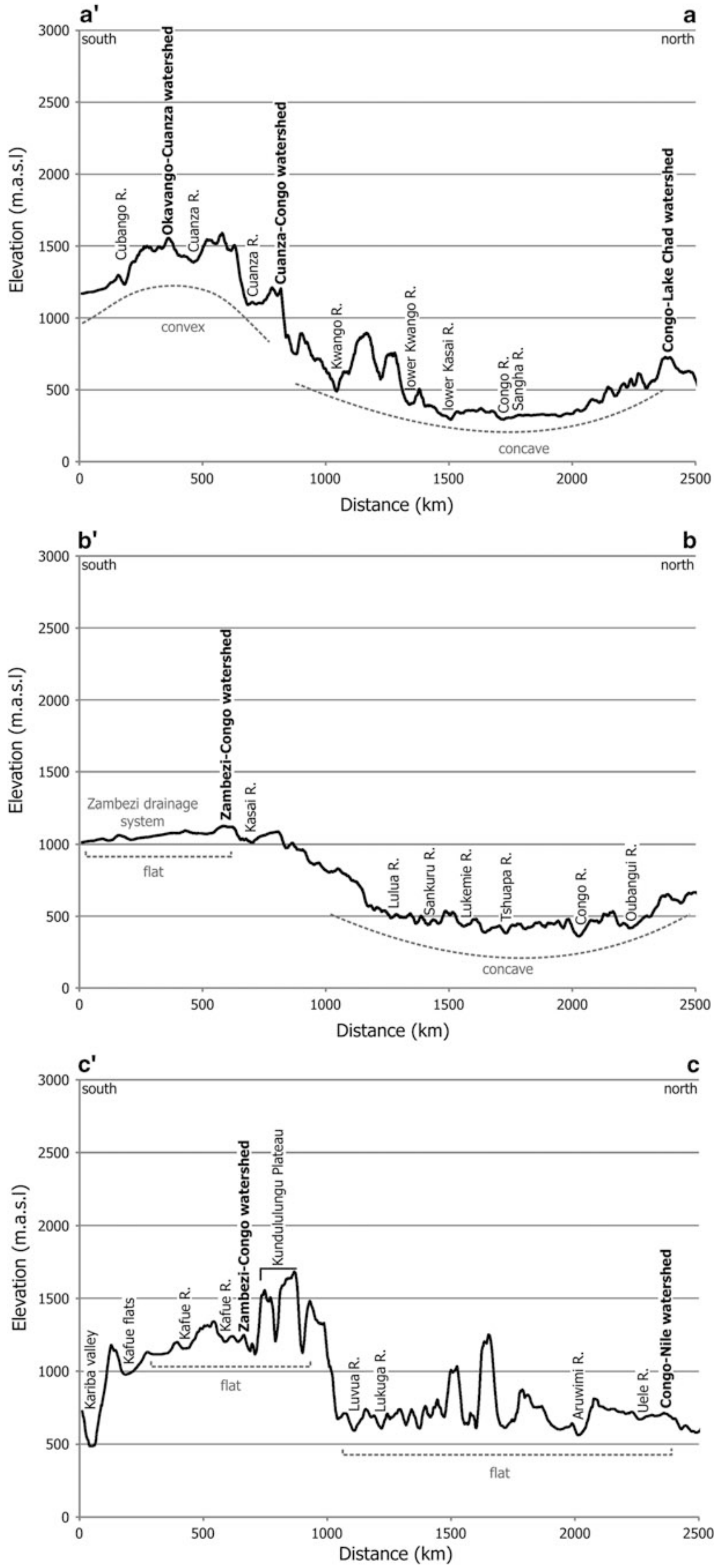

Fig. 15.6 (**a**) The western most cross section from a (north) to a' (south) with the location of major rivers and major watersheds (Okavango–Cuanza, Cuanza–Congo and Congo-Lake Chad) marked in *bold*. Note the convex topography of the Angolan Highlands region to the south and the concave profile to the north, which also includes the lower Kwango River. (**b**) The central north-south cross section depicting the gentle slopes of the CB system to the north and gradual transition towards a convex shape below the Zambezi-Congo watershed in the south. (**c**) Two first order landscapes are visible, a high, flat landscape at *ca*. 1,000 m.a.s.l in the south and a low, flat landscape at *ca*. 500 m. a.s.l. The high, flat landscape is punctuated by the topographic spike of the Kundulungu Plateau. The northern, low, flat landscape has several elevation spikes, representing the Western Branch of the EARS in the form of the eastern highlands of the Congo Basin. The trough of the Gwembe graben (Kariba valley) is conspicuous in the south. The watershed between the Zambezi-Congo and Congo-Nile are shown. The Kundulungu Plateau lies northward of the Zambezi-Congo watershed and is of a greater elevation than the watershed, representing a major deviation from the overall cross–section. The transition from the Zambezi to Congo system does not exhibit the general convex nature that is seen in the profiles further west (Fig. 15.6a, b), with rivers in the region incised to similar elevations

which is dominantly 1,400 m.a.s.l (with a maximum of *ca.* 1,600 m.a.s.l) compared to the rest of southern basin; as are the uplifted plateau separating the lower regions of the Mweru-Lufira-Upemba Complex. To the east of cross-section C, in the NW trending portion of the Western Rift lies the Tanganyika-Rukwa-Malawi (TRM) Rift (Fig. 15.5). The TRM is arranged in a rectilinear en-echelon array that reflects its formation in one of the most seismically active regions of the EARS with several active faults and ongoing seismic activity affecting most of the crust to ~30 km depths (Delvaux et al. 2012). The central zone of the TRM incorporates the well-defined Rukwa basin and the west bounding Ufipa Plateau. The tilted block comprising the Ufipa Plateau was uplifted during the late Cenozoic, largely within the Ufipa terrane (Delvaux et al. 2012). Here alignment of inselbergs and the footwall of faults systems illustrates the multi-stage tectonic history of the region (Delvaux et al. 2012).

The central zone of the CB is likely less erosively active than either of the western and eastern regions, although the convex nature of the transition from the Zambezi basin (high Africa) to the CB (low Africa) implies ongoing erosion. The flat nature of the Zambezi drainage system headwaters suggests limited vertical incision while the concave nature of the CB provides a depositional environment for material eroded from the convex southern headwater regions (Fig. 15.6b). The magnitude of this fluvial action in the central zone appears to be less than that occurring in the western zone, as indicated by the rough topography and deeply incised river valleys of the Kwango and Cuanza in the region of the Angola Highlands (Figs. 15.2 and 15.6a). While the overall concave nature of the central basin suggests a zone of sediment accumulation, the flat nature of the basin north of the Congo and Sangha Rivers suggest horizontal reworking of sediment rather than deposition (Fig. 15.6a). In the east of the CB, the incised river valleys indicate that vertical fluvial incision is dominant, and interestingly many of the rivers have incised to similar channel elevations (Fig. 15.6c). The overall flat nature of the elevated, high Africa region in the south and flat low Africa in the north indicates that these are dominantly sediment transition zones (Fig. 15.6c). The three cross-sections suggest that the eastern basin a zone dominated by vertical river incision and sediment transport, with the central is basin is more balanced between vertical river incision and sediment transport and deposition (Fig. 15.6b, c). In the west the central basin regions provide a sediment sink and horizontal sediment reworking is dominant, while in the south vertical river incision is active in regions (Fig. 15.6a). The implication for drainage pattern development is that, generally the eastern regions are likely to experience more frequent river re-organisation while the central and western regions patterns are, overall more established.

15.3 Present Day Drainage Patterns of the Congo Basin

The complex nature of the Congo Basin's hydrographic network was recognised by pioneering geologists (Veatch 1935; Roberts 1946; Cahen 1954) especially the evidence for the juxtaposition of several, apparently disparate, drainage patterns. It is believed the entire drainage network of the Congo Basin has been active since the late Cretaceous (Roberts 1946; Cahen 1954; Deffontaines and Chorowicz 1991; Goudie 2005). Deffontaines and Chorowicz (1991) have suggested that much of the present day drainage is superimposed, having originated in the early Cenozoic, and Cahen (1954) suggested even older ages for substantial portions of the basin. Our classification of the Congo Basin's drainage patterns (Figs. 15.3 and 15.4, and Tables 15.1 and 15.2) made extensive use of the SRTM DSM (Jarvis et al. 2008) and satellite imagery, namely Landsat Enhanced 7 Thematic Mapper Plus. This DSM was used to generate river networks based on a 90 m pixel resolution. These river networks where than classified into their drainage types, making use of the finer scale satellite imagery (30 m pixel size) in ambiguous areas, such as boundaries and drainage type changes. This allowed for a greater differentiation of pattern types than was previously possible (i.e. Roberts 1946; Deffontaines and Chorowicz 1991). As drainage patterns have a number of controls, such as geology, tectonics and regional topography, they may have convergent and divergent development histories making the interpretation of drainage patterns challenging (Fig. 15.3 and Table 15.1). Furthermore, drainage patterns may represent the cumulative effects of multiple controls. Nevertheless it is possible, and informative, to classify such drainage patterns at a regional scale. Of special interest are the boundary zones between patterns which may be indicative of active geomorphic changes in the basin.

Regionally, the CRS may be divided into eight dominant drainage patterns (see Table 15.1) occurring as 18 discrete zones (Fig. 15.3). This consist of the basic (major) patterns of dendritic, parallel, trellis and rectangular (Zernitz 1932) and contorted (Howard 1967) patterns. Three additional modified patterns, (which are deviations from the basic pattern due to structural or topographic controls, or the transition from one basic pattern to another) were used, namely, sub-dendritic, sub-parallel and a rectangular-angulate compound (Howard 1967). Naturally, more drainage types would be recognised on finer spatial scales. Here modified and palimpsest patterns are of special interest as they may indicate tectonic activity, but as these patterns are more local in nature (Howard 1967), they have not been included in the regional classification. A brief summation of those patterns of interest is shown in Table 15.1. The

Table 15.1 The description of the major drainage types found in the Congo Basin and their most probable controls

Drainage type	Description of drainage pattern	Drainage pattern may indicate the following*
Dendritic	Drainage is irregular, with channels branching in all directions and tributaries joining the main channel at all angles. Drainage is only truly dendritic if the main channels show no slope control. It has the widest modifications of all the basic drainage types	Tectonic stability; regionally uniform uplift or subsidence; low, uniform slopes; geology of uniform resistance; lack or weak structural control; horizontal lithology; superimposition (if occurring on folded or differentially resistant rocks or on a massive igneous body). As this drainage may be the result of several structural conditions, it is of limited use in determining geologic structure compared to other drainage types
Sub-dendritic	Deviation of dendritic	Modification most commonly due to secondary regional controls of structure and topography; transition phase of drainage
Parallel	A number of rivers and streams flow parallel, or near parallel, to one another over a considerable area, or in several successive cases. Parallel drainage may occur as a transition phase of dendritic or trellis drainage	Regional tilting; steep gradients (often on homogenous lithology); parallel topographic features; parallel faulting; transition phase of dendritic or trellis drainage. Parallel drainage may also indicate recent tilting, especially on newly emerged surfaces or may zones of parallel faulting. The parallel pattern suggests homogeneous sediment, with river following the greatest slope
Sub-parallel	Lack regular pattern of parallel drainage. However the distinction between sub-parallel and sub-trellis may be disputed	Slope changes; high relief slopes; mild structural control (i.e. deformed strata of uniform resistance to erosion)
Trellis	A trellis drainage is characterised by the occurrence of secondary tributaries parallel to the major stream or other streams into which primary tributaries enter. The secondary tributaries are often elongated, orientated at right angles to the streams into which they flow. Several modified types of trellis drainage exist, but require relevant data exists to determine their cause. For example fault and joint patterns appear similar. For this study patterns were categorised as trellis although there may be differences in control	Active faulting; the boundary of lithologies of varying resistance (i.e. parallel belts of folded or tilted strata); faulting; lithological jointing
Rectangular	Rectangular drainage is characterised by right-angle bends in both the main channel and its tributaries. It lacks the regular pattern and shorter tributaries that defines trellis drainage	Right-angle channel bends may be due to orthogonal joint or fault systems but lack regularity. Tectonic stability; regionally uniform uplift or subsidence; highly complex fractured systems; ongoing faulting
Rectangular-angulate	A common modified, compound version rectangular drainage but one where the pattern is dominated by non-right angle faults	Modified rectangular drainage where faulting is not dominantly right angled; ongoing faulting
Contorted	Lack a regular pattern, with tributaries exhibiting a multitude of flow directions	Deformed rocks (especially coarsely layered metamorphic rocks) that contain resistant layers (i.e. dykes and migmatised bands); stream and tributary length may indicate general direction of dip, making it possible to distinguish between plunging anticlines and synclines on the local level

Controlling factors are from Zernitz (1932) ; Howard (1967); Deffontaines and Chorowicz (1991) and are given in decreasing order of probability

Table 15.2 Regional drainage pattern classification of the Congo Basin. See Fig. 15.3 for the location of each drainage type

Drainage type	Map code	Location	Example of drainage type from the Congo Basin
Dendritic	D	Dominantly the (D1) Northern Oubangui, (D-Sd2) *Cuvette Central* and (D3) the Upper Malagarasi systems	Figure 15.4A
Sub-dendritic	Sd	Three zones surrounding the Central Basin and parts of the (D-Sd2) *Cuvette Central* ; (Sd4) the Western Congolain wetlands, and in the east the (Sd5) Lindi and (Sd6) Luvua systems	Figure 15.4B
Parallel	P	The (P7) Luangwe System of southern plateau lands of the basin including the middle Kasai	Figure 15.4C
Sub-parallel	Sp	The (Sp8) Northern Batéké Plateau System	Figure 15.4D
Trellis	T	Five systems, three of which are form the western boundary of the basin, *viz*. (T9) southern Batéké Plateau, (T10) Sembe-Ouesso and (T11) Kwango Valley systems. The (T12) Lufupa system forms the extreme southern basin boundary and the (T13) Mid-Congo River zone in the central basin	Figure 15.4E
Rectangular	R	Only the (R14) Buhimay System is the only rectangular pattern, being found in the Katanga region	Figure 15.4F
Rectangular-angulate	RA	The (RA15) Lulwango and (RA16) Ulindi systems are found on the western zone of influence by the EARS	Figure 15.4G
Contorted	C	The (C17) Lower Congo in the extreme west of the basin and the (C18) Lake Tanganyika / EARS in the eastern basin	Figure 15.4H

individual drainage patterns will now be discussed in more detail. Figure 15.3 indicates the extent and location of the various drainage patterns for the CRS and Table 15.2 provides the names and map codes of each drainage type and an example of the drainage pattern from the CB is illustrated in Fig. 15.4.

15.3.1 Dendritic Patterns

In the CB there are three regions exhibiting dendritic patterns and four exhibiting sub-dendritic patterns (see Table 15.2 and Figs. 15.3 and 15.4A):

15.3.1.1 Northern Oubangui System (D1 in Fig. 15.3)

This large, northern area of the basin appears to correspond to the underlying Precambrian basement (Chap. 2, this book). The occurrence of fractured, weathering resistant Proterozoic quartzitic sandstones provides localised structural control on some tributaries (Runge 2007).

15.3.1.2 Cuvette Central (D-Sd2 in Fig. 15.3)

The drainage pattern of the *Cuvette Central* is dominantly dendritic, although several large extents of interleaved sub-dendritic drainage patterns are present. Cahen (1954) suggested a Neogene to early Quaternary age for the large portions the *Cuvette Central* dendritic pattern and that portions of present day channels of the Sangha, Oubangi and Congo Rivers that flow through the Western Congolian wetlands, along with the Lukemie River, are related to the formation of Malebo (Stanley) Pool (Fig. 15.5). These sections thus represent the youngest part of the network (Cahen 1954). It is likely that portions of the *Cuvette Central* have been superimposed, flowing along inherited older trends (Deffontaines and Chorowicz 1991).

15.3.1.3 Upper Malagarasi System (D3 in Fig. 15.3)

The upper Malagarasi system exhibits a dendritic pattern. The dendritic pattern lies predominantly on Tanzanian cratonic region, in the shallow basin region south of Lake Victoria. The tectonic stability and broadly uniform lithology this region would have allowed for the uninterrupted development the Malagarasi system.

15.3.2 Sub-dendritic

15.3.2.1 Cuvette Central (D-Sd3 in Fig. 15.3)

There are several of zones of sub-dendritic drainage that occur within the overall dendritic pattern of the *Cuvette Central*. This sub-dendritic drainage dominantly occurs in the western, eastern and southern zones of the *Cuvette Central* (see Table 15.2 and Figs. 15.3 and 15.4B). Several of these zones are associated with areas of locally outcropping resistant lithologies and structure, in a region that is dominantly alluvial in nature. Abrupt changes in flow direction in zones of transition from one dendritic to sub-dendritic patterns reveal the presence of NE–SW and ESE–WNW trending faults (Deffontaines and Chorowicz 1991). Additionally, to the south, the Lukémié and Kasai Rivers have parallel interfluves that suggest the modification of river patterns by a horst block or tilted block (Deffontaines and Chorowicz 1991). The abrupt change in river direction of the Congo River near Kisangani, the middle section of the Sankuru River and also in the lower Kasai to the south such structural controls, which have experienced vertical movements since the Cenozoic (Figs. 15.1 and 15.5; Deffontaines and Chorowicz 1991). The regular, trending to parallel drainage pattern of the lower Kasai River in the south, may indicate a distinct, major block tilted northwards (Deffontaines and Chorowicz 1991).

15.3.2.2 Western Congolian Wetlands (Sd4 in Fig. 15.3)

The drainage pattern of the rivers flowing south into the CR just before it crosses the Equator for a second time is sub-dendritic. This drainage zone corresponds to a large, inundated region of dominantly Holocene alluvium that forms the Western Congolian wetlands. A combination of low gradients and mosaics of very dense tropical rainforest and swamplands has prevented the establishment of dendritic drainage. This can be seen in the multi-branching meandering form of Likoula aux Herbés River (a tributary of the lower Sangha River, Fig. 15.5) as it flows through the wetlands. Parts of the region have be influenced by neotectonics (namely Lac Télé (Master 2010) which has likely further inhibited the development of a dendritic pattern through network reorganisation.

15.3.2.3 Lindi System (Sd5 in Fig. 15.3)

This small zone of sub-dendritic drainage occurs in the north-east of the basin with trellis and dendritic drainage lying on the downstream side to the west and north, while rectangular angulate and contorted drainage occurs upstream in the southern and eastern sections. The Lindi systems thus appears to be influenced both by the structural influence of the EARS to the west and the trellis network of the downstream mid-Congo. It is possible that the Lindi System was part of the *Cuvette Centrale* and Luvua (sub) dendritic system and has been subsequently isolated by downstream capture and modified by the EARS in its headwater zones.

15.3.2.4 Luvua System (Sd6 in Fig. 15.3)

The Luvua system occurs in the south-western areas of the Congo Basin and extends northward along the CR. The

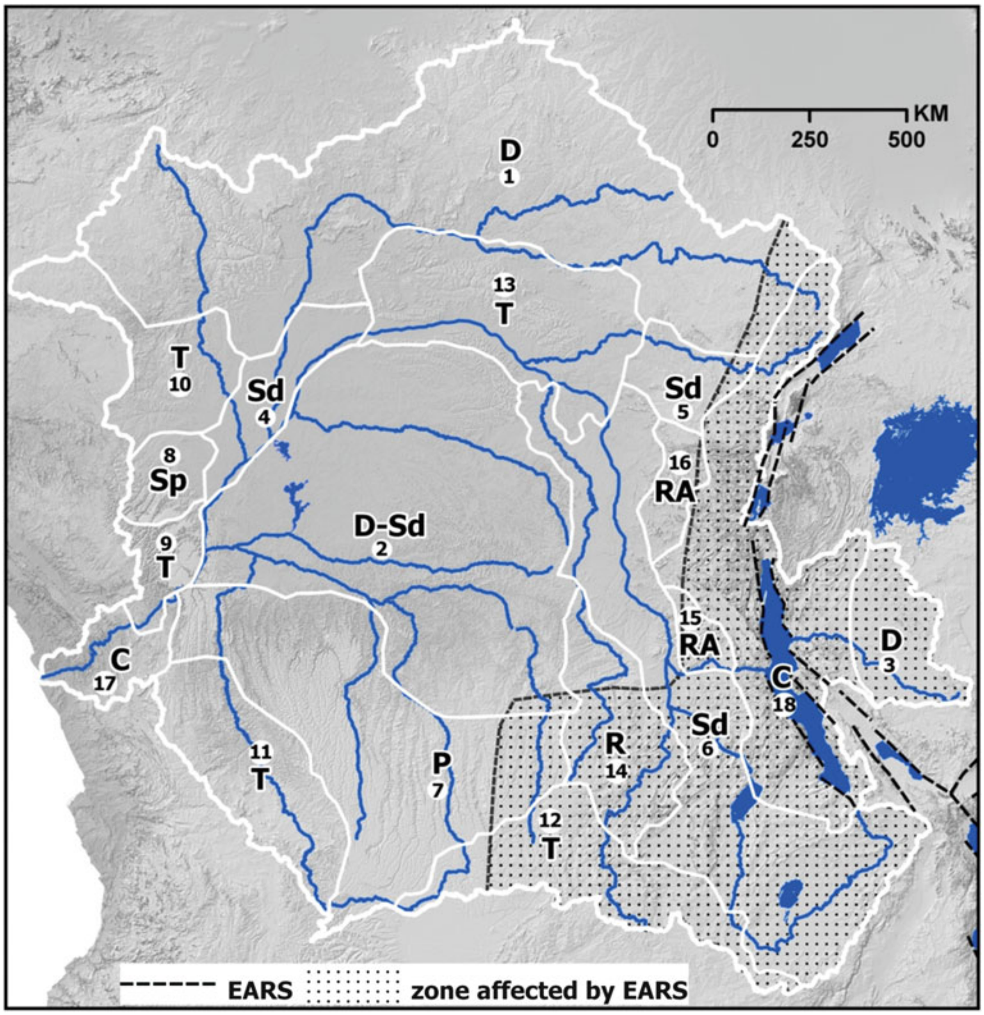

Fig. 15.7 The EARS (*black dashed lines*) and its affect on the CB drainage patterns. The stippling indicates the regions of the CB that been affected by seismic activity linked to the EARS. Drainages close to the rift are most affected by seismic activity, which has a calculated extent of up to 450 km west of the EARS. At distances greater than 450 km, the probability of a seismic event exceeding a peak ground acceleration (PGA) of 0.05 g is less than 10 % in 50 years (Mavonga and Durrheim 2009). This relative higher probability and greater PGA of seismic events closer to the rift could account for the occurrence of Sd5 (Lindi), RA15 (Lulwango), RA16 (Ulindi), Sd6 (Luvua), R14 (Bushimay) and T12 (Lufupa) networks. The limited affects on D3 (Upper Malagarasi) may be related to its proximity to a cratonic region. Interestingly the lower region of the Malagarasi river has become contorted (C18)

southern reaches have a dominant south-west orientation, suggesting some degree of structural control in the region. A large portion of this zone corresponds to the Precambrian basement (Deffontaines and Chorowicz 1991); with evidence of recent tectonic activity along Lake Mweru and a wide alluvial plain upstream of the lake, near Kasenga (Tack et al. 2003). This tectonic activity, associated with the Western Branch of the EARS, is the probable explanation of the sub-dendritic pattern in this region (Fig. 15.7). The similar morphologies of the Ufipa Plateau and Rukwa basins (north of the Chambeshi headwaters, in the Tanganyika-Rukwa-Malawi rift zone) to the Kundelungu Plateau and Lake Mweru provide further evidence of tectonic control of the drainage (Fig. 15.5). While the Rukwa Plateau is generally tilted towards Lake Tanganyika, several of its rivers drain into Lake Rukwa, possibly reflecting a combination of antecedence and tectonic control of these rivers (Delvaux et al. 2012). Additionally there appears to be no river offsets across the scarps (Delvaux et al. 2012). The importance of tectonic events in the region is illustrated by 1910 earthquake in the region that is estimated to have been 7.4 in magnitude (Delvaux et al. 2012). Similarly, localised faulting and uplift appears to have morphed the dendritic network into a sub-dendritic pattern. In summary, much of the sub-dendritic pattern represents the interplay between the inherent structural controls of the Precambrian basement on the one hand, and extensional movements of Neogene to late Holocene age, as is suggested for the Upemba Trough (Fig. 15.5; Deffontaines and Chorowicz 1991). This may be further enhanced by rift associated uplift that promoted erosion and incision of the pre-rift sediment and/or basement, with this rift flank induced river system draining into the basins (i.e. Mweru) in structurally low-lying regions between fault segments.

15.3.3 Parallel

Within the CB, two areas exhibit parallel type drainages: the parallel drainage of the southern plateau region of the basin, as seen in the Luangwe System and the sub-parallel drainage of the Northern Batéké Plateau System of the basin western margin (see Table 15.2 and Figs. 15.3 and 15.4C) .

15.3.3.1 Luangwe System (P7 in Fig. 15.3)

The southern plateau areas, which incorporates the Luangwe basin and associated tributary catchments in the southern Basin has dominantly parallel drainage pattern. The boundary zone varies from parallel to sub-parallel and it covers a region that has been suggested to have remnants of an upper Jurassic drainage network (Cahen 1954). The parallel drainage is associated with the transition zone of the low gradient slopes of the northern extent of the Kalahari Plateau to the basin of *Cuvette Central*. The parallel pattern suggests uniform lithology which allows the river to flow along the greatest slope, as seen to the south of Kasai (Zernitz 1932; Deffontaines and Chorowicz 1991).

15.3.4 Sub-parallel

15.3.4.1 Northern Batéké Plateau System (Sp8 in Fig. 15.3)

The Northern Batéké Plateau System comprises of many near linear rivers, flowing across a NE dipping plateau (see Table 15.2 and Figs. 15.3 and 15.4D). The combination of the a strong NNE flow direction and the linearity of the rivers with connections between parallel rivers being short suggests a degree of fault control. The location of the plateau to the Atlantic margin, lead Karner and Driscoll (1999) to suggest a Gondwana break-up origin of these rivers. These rivers may have begun flowing basinward due to flexural rebound associated with Gondwana break-up, that established numerous, short rivers toward the interior basin (Karner and Driscoll 1999) and these patterns have been maintained to present day.

15.3.5 Trellis

There are five instances where trellis drainage was identified, with this drainage type occurring mainly along the peripheries of the central basin (see Table 15.2 and Figs. 15.3 and 15.4E).

15.3.5.1 Southern Batéké Plateau System (T9 in Fig. 15.3)

The Southern Batéké Plateau System differs from the Northern Batéké Plateau System in that the rivers in the region are shorter, with more right angles and flow directly into CR. The geometry of the rivers and the consistent directionality of many of the river segments, being WWN, reveal a dominant fault control. Additionally much of this zone corresponds to the Precambrian basement (Deffontaines and Chorowicz 1991), which incorporates a portion of the West Congolian orogenic belt making it probable that tectonics, lithological structures and rock differences, have resulted in a trellis drainage forming. Subsequent tectonic activity may have modified the rivers further.

15.3.5.2 Sembe-Ouesso (T10 in Fig. 15.3)

This pattern is controlled by numerous south-north trending faults, with several NNE trending faults, with the rivers flowing on Precambrian basement. Dolerite outcrops further add to the structural control of this trellis pattern. Therefore the Sembe-Ouesso drainage network is predominantly controlled by the directionality of the faults, and the underlying lithology.

15.3.5.3 Kwango Valley (T11 in Fig. 15.3)

The Kwango Valley, found along the southern margin of the CB exhibits a trellis pattern drainage pattern. Here the Kwango River flows in a north-west direction, compared to parallel, north flowing rivers of adjacent Luangwe System to the east. Incision into the Precambrian basement by the Kwango River appears to have caused the diversion and breakup of the longer parallel streams into several shorter rivers. Thus the Kwango River trellis pattern, at least in the eastern region close to the Luangwe System, likely represents a modification of a parallel drainage that existed on the tilted plateau, previous to incision by the Kwango River. Furthermore, its location on the margin of the West Congolian orogenic belt has resulted in the western part of the Kwango Valley developing a strong trellis pattern, shaped by structural control in this region. The Kwango Valley drainage therefore is dominantly a modified parallel network with subsidiary structural control.

15.3.5.4 Lufupa System (T12 in Fig. 15.3)

Forming the southern margin of the Congo Basin the Lufupa trellis drainage system comprises of the easterly flowing Kasai River in the west and the northerly flowing upper Congo (Lualaba) River in the east. The Lufupa system thus forms the main portion of the Congo-Zambezi Watershed. The western part of this trellis network, around the Kasai River, may contain the remnants of late-Cretaceous rivers (Cahen 1954) and thus it inherited to some degree. Whereas, the presence of folded schists and tillites of the Kanga-System (Upper Precambrian) and tectonics (indicated by three major fault scarps) (De Dapper 1988) in the eastern half of the trellis drainage are the likely controlling factors on the drainage pattern.

15.3.5.5 Mid-Congo River (T13 in Fig. 15.3)

The northern bank of the middle CR is dominantly trellised with the southern bank having numerous small rivers join the Congo at right angles. This start of the trellis network closely corresponds to the abrupt and localised braiding of the CR that begins at 0°24°E and continues until 1°N 16°E. The braiding of stream channels suggests an inability to transport the bed load. This may be due to local coarser bedload, and/or loss of velocity due to flattening of gradient (Howard 1967). It is likely that trellis pattern represents a modification of pre-existing dendritic network, as the middle Congo trellis network is bounded between the northern Oubangui and central basin dendritic networks. This modification could be related to the capture of the lower CR. It is probable that this trellis pattern has been enhanced by local structural controls such as exposed outcrops of basement.

15.3.6 Rectangular

The CB contains a single zone of rectangular drainage, this being found in the south-east region of the basin (see Table 15.2 and Figs. 15.3 and 15.4F).

15.3.6.1 Bushimay System (R14 in Fig. 15.3)

The rivers in this zone have a general north-northeast orientation, bounded in the west by a high ridge, which separates the upper CR (also referred to as the Lualaba) from the Kasai system (Cahen 1954). Roberts (1946) suggested that these north-northeast river courses exhibit strong inheritance, where they occupy Karoo palaeovalleys. The persistent seismicity all around the Upemba Trough attests to Neogene to Recent extensional movements (Deffontaines and Chorowicz 1991). Therefore this area is likely a zone of intense faulting.

15.3.7 Rectangular-Angulate

There are two zone of rectangular-angulate drainage, both relatively small and located in the eastern CB in proximity of the Western Branch of the EARS (see Table 15.2 and Figs. 15.3 and 15.4G).

15.3.7.1 Lulwango (RA15 in Fig. 15.3)

The Lulwango system, is a small area, with a mixture of channels with right-angle bends and channel junctions forming acute angles. The combination of NE–SW trending, linear ridges and Basement rock outcrops appears to be the local controls of the drainage. The linear ridges have resulted in channels running near parallel in part, forming right-angles as they cut across the ridges. Additinoally as the sub-dendritic Luvua System (Sd6) lies to the south and west (downstream) and the contorted Lake Tanganyika (C18) to the north and west (upstream) the Luluwango system exhibits both structural and tectonic controls evident in these systems. It is probable that the Lulwango system is an area of ongoing modification, forming a zone of interaction between the Luvua and Lake Tanganyika systems. The multiple phases of deformation and rejuvenation experienced by the Western Branch (Cahen and Snelling 1966) has likely enhanced rectangular-angulate pattern (Fig. 15.7). The interaction of these factors likely accounts for the system having deviated from a topographically controlled (linear ridges) trellis or rectangular pattern.

15.3.7.2 Ulindi (RA16 in Fig. 15.3)

The Ulindi system is surrounded by the sub-dendritic systems of the Lindi (Sd5) and Luvua (Sd6) to the north and west (downstream), with the contorted drainage of Lake Tanganyika (C18) being to the south and north (upstream). The drainage exhibits is more rectangular compared to the Lulwango but lacks perpendicular channel junctions and. It is likely that the outcropping Basement rocks providing a degree of structural control, with the Western Branch having a limited, direct influence on the Ulindi system (Fig. 15.7). Occurring between two dominant drainage types (sub-dendritc downstream and to the north; contorted upstream and to the south) this modified pattern forms a interface zone between the two drainages.

15.3.8 Contorted

In the CB contorted drainages are associated with two zones of deformation, the Atlantic Rise and the EARS (see Table 15.2 and Figs. 15.3 and 15.4H).

15.3.8.1 Lower Congo (C17 in Fig. 15.3)

The contorted drainage of the Lower Congo corresponds to the area where the CR and its associated tributary rivers straddle the Western Escarpment and the coastal region of the CR. Here, the river morphology appears to be controlled dominantly by the exposure of Precambrian rocks; the contorted drainage follows the various zones of the West Congolian orogeny. It is likely that tectonic activity, combination of uplift (thought to be more than 300 m) and warping and/or tilting, associated with the Miocene reactivation of the West African margin, resulted in drainage reorganisation, further enhanced the contorted drainage pattern (Cahen and Snelling 1966; Lavier et al. 2001). It has been suggested that increased sediment loading on the coastal shelf during was the cause of this tectonic reactivation (Deffontaines and Chorowicz 1991; Driscoll and Karner 1994; Anka and Séranne 2004; Anka et al. 2010).

15.3.8.2 Lake Tanganyika/East African Rift System (C18 in Fig. 15.3)

The eastern margin of the CB is dominated by a contorted drainage pattern. The area of contorted pattern corresponds to the Eastern Highlands and thus forms the headwater zone of many of the westerly flowing rivers. The streams and rivers of this zone lack a consistent drainage pattern, with rivers flowing in several different directions and near-straight channelled rivers flow adjacent to rivers. This lack of consistent pattern indicates a dominance of fault and lithology controls in the region. The fact that much of this drainage system corresponds to the Western Branch of the EARS, it is likely that much of the drainage has been influenced by phases of tectonic activity (Fig. 15.7). Indeed several phases of tectonic activity have been identified, resulting in the overprinting of faults by succeeding faults and the formation of valleys and regional blocks (Cahen and Snelling 1966; Ring 2008; Bauer et al. 2010). In the Rwenzori Mountains (Fig. 15.2), the Precambrian basement rocks widely resist fluvial erosion, causing the rivers to predominantly exploit predetermined structures (Bauer et al. 2012). It is thus likely that the contorted drainage pattern is strongly linked to the ongoing tectonic activity associated with development of the Western Branch. For example, the uplift of the Ufipa Plateau severed the drainage linkages to the Tanzanian Plateau in the east, notably those of the greater Rufiji drainage system (Fig. 15.1A). This uplift appears to be Pliocene in age (e.g. Cotterill and de Wit 2011; Goodier et al. 2011).

Therefore a large portion of Lake Tanganyika's drainage is geological young and fault controlled, with the contorted pattern being related to a combination of multiple phases of uplift, subsidence, tectonic activity and exposure of Precambrian rock. This is distinctly seen in the lower Malagarasi (Fig. 15.2) and Lukuga systems that drain into and out of Lake Tanganyika respectively. The Malagarasi systems changes from a dendritic pattern to a contorted pattern in the zone where the river begins to flow off craton and becomes influence by rifting. Previous to the formation of the Western branch there was greater linkage between the drainage of Eastern Africa and the CB. This palaeo-channel is represented in the topological unity of modern Malagarasi River, draining into Lake Tanganyika. These preserved landforms attest to the profound impact of the EARS, in particular its Western branch, on the evolution of the eastern rivers of the CRS (Fig. 15.3).

15.4 Timing of Emplacement of the Modern River Systems of the Congo Basin

15.4.1 Cenozoic Events

The marine sedimentary evidence lead to the suggestion of several scenarios of CB evolution. The three models proposed to account for this marine sedimentary record are : 1) at the end of the Cretaceous there was a progressive change of the depocentre from the Ogoué and Cuanza (Kwanza) Rivers to the Congo as a result of capture of the endorehic Congo Basin (Babonneau et al. 2002; Anka et al. 2010). Today these southern and northern systems exhibit multiple incised valleys and gorges along the coastal areas, often occupied by under fit river channels. 2) There was a net southward migration of the outlet of the CRS from the Cretaceous to the Cenozoic (Karner and Driscoll 1999; Nibbelink and Budihardjo 2002). During the late Cretaceous, the entire CB was drained by an outlet at or near the present day Ogoué River (northern Gabon) (Karner and Driscoll 1999; Nibbelink and Budihardjo 2002). Through the mid-Cenozoic the outlet migrated south, forming a connection near/at the present day Kouilou River, reachingthe present day CR outlet in the Oligocene (Karner and Driscoll 1999; Nibbelink and Budihardjo 2002). Karner and Driscoll (1999) suggest that feedbacks between sediment loading and flexural uplift of the hinterland may have played a role in the migration of the outlet, although the mechanism of migration is unclear. This migration may be evidenced in the misfit of the present Ogoué and Kouilou Rivers (see Fig. 15.1a, c, the Kouilou River is near Point-Noire Fig. 15.1c) that occupy abandoned channels and their valleys, relic drainages and the large estuary near Liberville and the large size of the Late Cretaceous—early Cenozoic delta along the Gabon coast relative to present-day coastal river systems (Karner and Driscoll 1999). This tectonic activity may have lead to the capture of the interior drainage of the Congo Basin by a coastal valley (Cahen 1954).The lower CR crosses an area of lower modelled flexural uplift (Anka et al. 2010) suggesting that the lower Congo River comprises of inherited drainage. This antecedent lower CR is evidenced by the deeply incised gorge and waterfalls downstream of Kinshasa (Anka et al. 2010).

15.4.2 Neogene Events: Evidence from Phylogeographic Studies of Fishes and Mammals

While there is some geologic and geomorphic data regarding the timing of river re-arrangements, this data is often discontinuous or lacking in terms of resolution. This lack of data of river developments can be circumvented by using biological data as proxies to identify changes to drainage topology. These proxies use phylogenetic reconstructions of related species that have become geographically isolated by changes in the landscape in which they live. Over evolutionary time, the isolated populations accumulate changes in their DNA, with the genetic difference between the populations allowing for an estimation of time since separation based on a molecular clock (Avise 2000; DeSalle and Rosenfeld 2013). It is possible to determine the average rate at which a species has accumulated genetic differences (mutation rate) over time. By measuring the number of genetic differences between two related groups and applying the average mutation rate, a time estimate of when the two populations were once freely breeding can be calculated (Avise 2000). This process gives the approximate age of genetic divergence of the two groups from their last shared common population, or most recent common ancestor (MRCA) (Avise 2000). The use of Bayesian methods allows for age estimates to be assigned a measure of statistical error, usually expressed at the 95 % level, which constrains the probability of the true age value (DeSalle and Rosenfeld 2013).

The challenges involved in using phylogenetic data (such as calibration methods and sampling density of species) can be mitigated by using phylogenetic data from several species. The congruence of age estimates across different species provides insights into the spatio-temporal changes in the fluvial geomorphology of central Africa during the late Cenozoic (i.e. Cotterill and de Wit 2011; Goodier et al. 2011; Schwarzer et al. 2011; Hart et al. 2012; Kawamoto et al. 2013). For example, it appears that the CR is the only river that contains the extent of the large primates, namely chimpanzees (*Pan troglodytes*) and gorillas (*Gorilla gorilla*), preventing these primates from occurring south of the CR, although both having successfully dispersed across smaller rivers (see Fig. 15.8a). Fish are the most accessible of these biological indicators and being restricted to water systems their biogeography and evolution are tightly linked to the evolution of fluvial systems (Cotterill and de Wit 2011). This link of biogeography and landform can be seen in the broad congruence that difference fish assemblages show with regional drainage basins. Although fish assemblages may differ locally, owing to the interplay of numerous abiotic and biotic factors (i.e. water pH, temperature, biological competitors and predators) some fish species occupy definitive niches (stenotypes), and are thus forced to track their local environments. Over evolutionary timescales, these stenotypes either successfully track their specific physical habitats, or become extinct. Therefore stenotopic fish may record the timings of river events, such as disruption or connections of river channels, when water transfer between the river systems ends or begins. The events dates by molecular proxies, record of the start of the current phase of the river drainage structuring (assuming equal ability of dispersal up and down rivers, that is no barriers) as connections may be seasonal (i.e. yearly flood) or event based (i.e. 1 in 10 year floods). The use of primate evidence goes some way in solving problems with the timing of prolonged river channel emplacements as many primate taxa distribution patterns are often contained by major rivers that serve as barriers to movement, both on a genus and species levels (Anthony et al. 2007; Harcourt and Wood 2012).

Yet not all rivers are equally effective barriers, with wider and faster flowing rivers being formidable barriers compared to narrower, smaller tributaries and thus the lower reaches of a river are often more effective barriers compared to their upper reaches; for example, the lower sections of the CR seem to be more effective barriers than its smaller tributaries and headwaters (Harcourt and Wood 2012). As African rivers form the border of distributions for more subspecies rather than genera, Harcourt and Wood (2012) suggest that primate taxonomic level may be a useful, albeit rough, proxy to estimate times of population isolation by river emplacement. Therefore primate divergence estimations (calculated from the MRCA) may serve as proxies of rivers achieving a sufficient size, and continuity of flow, to become a barrier to dispersal. The CR acts a major, regional barrier to primate dispersal, with fewer primate species and subspecies straddling the CR compared to other rivers (Harcourt and Wood 2012). Owing to the relationship between rivers as a barrier and primate size (Harcourt and Wood 2012), it can be argued that timings of divergence of large primates (i.e. bonobos, chimpanzees and gorillas) relate to the development of large rivers (i.e. Congo) with medium and smaller primates serving as proxies for emplacement of medium and smaller rivers. However the inherent heterogeneity of a river in both space and time must be borne in mind when considering rivers as barriers to primate dispersal. This is highlighted by a genetic study of chimpanzees either side of the Malagarasi River, an assumed barrier river (Piel et al. 2013). Although the Malagarsi River is over 100 m wide for extensive stretches, both field observations and genetic analysis of chimpanzees populations either of the river, close to a ford, indicated that the chimpanzees made use of this natural bridge to cross the river (Piel et al. 2013). Thus the Malagarasi River is likely only a seasonal barrier to primate movement in areas where natural rock bridges may have

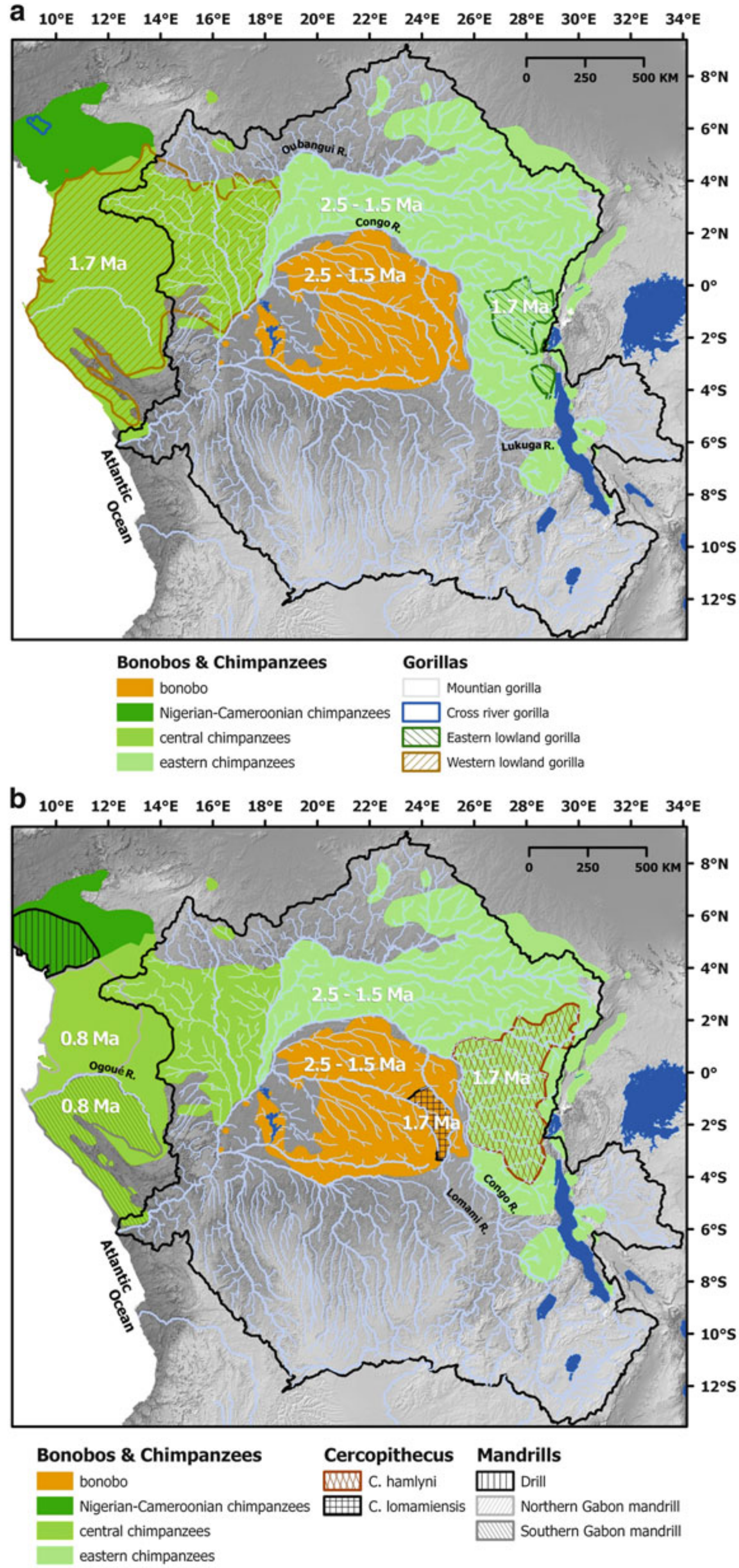

Fig. 15.8 (**a**) The geographical distribution and molecular divergence dates of bonobos, chimpanzees (Genus *Pan*) and gorillas (Genus *Gorilla*), in central and western Africa. The Lukuga River (outflow of Lake Tanganyika) appears to have become a recent barrier to eastern chimpanzees (modified from Prüfer et al. 2012; Scally et al. 2012). Chimpanzees (*green*) and bonobos (*orange*) were separated by the Congo River between 2.5 and 1.5 Ma; and the western and eastern gorillas show an analogous divergence at *ca*. 1.7 Ma. (Bonobo, chimpanzee and gorilla distributions derived from UNEP-WCMC and IUCN International Union for Conservation of Nature 2008a, b, c. (**b**) The geographical distributions of bonobos, chimpanzees, guenons (Genus *Cercopithecus*) and mandrills (Genus *Mandrillus*). See Molecular divergence dates of the southern and northern mandrills of Gabon in the west suggest that the present day Ogoué River became established 0.8 Ma (Telfer et al. 2003). To the east of the CB, divergence dates suggest that the guenon populations were separated by the Lomami – Congo rivers at 1.7 Ma (Hart et al. 2012). See Fig. 15.8a for congruent biogeographical patterns in of bonobos and chimpanzees

allowed gene flow (Piel et al. 2013). Similar situations may be found for other rivers of the CRS with more extensive and intensive field research. Ultimately information on paleo-environmental changes in the CB during the late Noegene and Quaternary are required to fully elucidate the genetic structure of many of the primates in the basin (i.e. Kawamoto et al. 2013). Furthermore, the geographical pattern of a primate grouping may take hundreds of thousands of years to develop (i.e. Kawamoto et al. 2013), thus requiring rivers to be effective barriers during the entire period.

This also means there will be a lag time from when a river becomes a barrier and its effects are seen in the genetic signal.

15.4.2.1 Phylogenetic Age Estimates of Geomorphic Events

In central Africa, a synthesis of phylogenetic studies of primates provide an estimation of river emplacement (Fig. 15.8a, b; Table 15.3) in the Late Pliocene and Early Pleistocene. Evidence from the divergence of bonobos-chimpanzees suggests that the Equatorial arc of the Congo River was an effective barrier to large primate dispersal, with Prüfer et al. (2012) suggesting a 2.5–1.5 Ma, although a different genetic marker provides a 1 Ma age estimate (Kawamoto et al. 2013). The divergence estimate of 1.75 Ma for the western (*Gorilla gorilla*) and eastern (*G. beringei*) gorilla populations (Scally et al. 2012) suggests that the CR (and possibly the Oubangui) formed a barrier to gorilla dispersal at a similar time of the bonobo-chimpanzee divergence (Fig. 15.8a; Table 15.3). Genetic data for the lowland gorillas indicate a subsequent, moderate genetic exchange between the two groups, since the initial split suggesting movement of individuals between the two populations until the late Pleistocene; with the eastern population experiencing a genetic bottleneck that is indicative of low population numbers (Ackermann and Bishop 2010; Scally et al. 2012). Nevertheless both molecular and morphologically studies support the classification of the two species, eastern and western gorillas with further subdivision down to subspecies possible. This is further evidence for genetic structuring within the western and eastern gorilla populations, suggesting a barrier role of rivers smaller than the Congo River (Anthony et al. 2007; Ackermann and Bishop 2010) Yet more extensive sampling of both gorilla populations is needed to allow for better resolution of divergence times (Scally et al. 2012).

While the CR is an effective barrier to bonobos dispersal northward, almost all the dendritic to sub-dendritic drainage of the *Cuvette Central* (D-Sd2 in Fig. 15.3) have had little affect on gene flow between populations (cohorts), apart from the lower Lomami River (Fig. 15.5; Kawamoto et al. 2013). The barrier effect of the Lomami River is seen in the greater genetic distance of the bonobo cohort east of the river (the area between the Congo and Lomami rivers) compared to the central and western cohorts (Kawamoto et al. 2013). Additionally the genetic distances among the central and western bonobos cohorts suggest that in the central region of the basin that rivers only provide a weak barrier (Kawamoto et al. 2013).

The recently discovered species of guenon monkey in the genus *Cercopithecus* (*C. lomamiensis*), based on morphological and molecular evidence, provides proxy evidence of the emplacement of the Lomami River (Hart et al. 2012). *C. lomamiensis* is separated from its nearest congener, *C. Hamlyni*, by both the Congo and the Lomami rivers (Hart et al. 2012) (Figs. 15.5 and 15.8b; Table 15.3). *C. lomamiensis* is endemic to the region confined by the upper Tshuapa River in the west through to the Lomami River in the east, whilst the eastern-most distribution of *C. hamlyni* is bounded by the CR (Hart et al. 2012). Hart et al. (2012) suggest the Lomami and upper Congo rivers are the biogeographic barriers responsible for this speciation event. Molecular divergence dates estimate the time to MRCA of the *C. lomamiensis*–*C. hamlyni* clade based on two different genetic makers, provide age estimates of *ca*. 1.7 Ma (3.2–0.5 Ma at 95 % confidence level) and *ca*. 2.8 Ma (4.3–0.6 Ma at 95 % confidence level) respectively (Hart et al. 2012).

The congruence of the divergence data for the bonobos-chimpanzees, gorillas and guenon species, supports the emplacement of the modern, crescent shaped CR river by 1.5 Ma. The CR became an effective barrier to gene flow (i.e. larger than 100 m—assumed effective barrier size for chimpanzees see Piel et al. 2013) between 2.5 and 1.5 Ma based on the most recent common ancestor of bonbos and chimpanzees. This places an age constraint on the drainage pattern of the *Cuvette Central* (D-Sd2 in Fig. 15.3), with its relatively young age accounting for the mixture of dendritic and sub-dendritic features. The separation of *Cercopithecus* around 1.7 Ma by the northerly flowing Lomami River strengthens the emplacement age of the modern CR.

The north-western boundary of the CB is formed by the watershed between the Congo and Ogoué rivers is marked by the Batéké Plateau. The eastern portion of the plateau slopes gently toward the CR and is incised by numerous, actively eroding headwaters of tributaries of the Ogoué River (Seranne et al. 2008). Telfer et al. 2003 report a divergence time of the mandrill (*Mandrillus sphinx*) populations north and south of the Ogoué River at *ca*. 800 Ka, constraining the emplacement of the modern Ogoué River to at least 800 Ka. With a sediment load of 19.7×10^6 t a^{-1} the Ogoué River has a comparable sediment to the CR (22.7×10^6 t a^{-1}) although the Ogoué water volume is a magnitude less than the Congo's River, suggesting the Ogoué watershed is undergoing active erosion (Seranne et al. 2008). Thus the headwater regions of the Ogoué are actively incising backward, and have likely captured smaller north-western tributaries of the CR within the last 800 ka.

Table 15.3 The fluvial changes of in the Congo basin during the Neogene and Quaternary. The timing of events is based on age estimates reported by phylogeographic studies.

Period	Geomorphic event and time estimate	Phylogenetic evidence
Neogene		
Early to middle Miocene	(1) Diversion of north eastern Congo of the Aruwimi River headwaters drainage towards the Nile	(1a) "*Haplochromic*" species "Yaekama" is distributed in the north eastern CRS near Kisangani but groups with Lake Victoria superflocks (Schwarzer et al. 2012). (1b) A sistergroup of modern haplochromines found in Lake Kivu occurs in Lake Victoria (Schwarzer et al. 2012)
	(2) Major drainage re-organisations of central CRS drainage flowing off the southern escarpment with: (i) severance of connections between the Fwa, Inkisi and Kiwul Rivers (rivers presently adjacent to one another in south western CB); (ii) disruption of the Sankuru-Lukemie system, with diversion of present day Sankuru flowing into the Kasai system	(2a) Close phylogenetic relationship of "*Haplochromis*" species haplotypes of the Fwa-Inkisi-Kwilu Rivers (Schwarzer et al. 2012) (2b) Genetic markers of the Fwa "*Haplochromis*" closely related to these in the mid-Kasai and mid-Kwango Rivers and; Fwa haplochromides closely relates to "*H.*" cf *bakongo* and "*H.*" snoeki from the lower CR system (Schwarzer et al. 2012)
Late Neogene		
	(3) Partial re-arrangement across the headwaters of the Lufira, Kwango and Cuanza (an Angolan coastal basin) systems; capture of Zamnezian headwaters by the Lufira	(3) Hybrid taxa of northern and southern *Oreochromic torrenticolo* and *Serranochromis* sp. "red scales" that presently occur either side of the Congo-Cuanza and Congo-Zambezi divides (Schwarzer et al. 2012)
	(4) Approximately 4 Ma: Establishment of water flow across the modern day lower rapids of the CR connecting the CRS to the Atlantic Ocean (established by 5 Ma?)	(4) High level of cichlid flocks (*Steatocranus* and *Nanochromis*) diversification in the lower CR; these cichlids are endemic to rapids (Schwarzer et al. 2011)
	(5) 3.1 Ma : Disruption of drainage between Lake Tanganyika and Lake Victoria/East Africa drainage	(5) Phylogenetic dating of the timing of divergence of *Hydrocynus tanzania* and *H. vittatus* (Goodier et al., 2011)
Quaternary		
Pleistocene	(6) 2.5–1.5 Ma: Establishment of the 'modern', sickle shape of CR is established in the region of the Equator	(6a) Divergence date between chimpanzees occurring on the northern and eastern banks of the Congo River with bonobos restricted to an area inside the arc of the CR. Dates of 2.5–1.5 Ma (Prüfer et al. 2012). See Fig. 15.8a (6b) Divergence age between western and eastern gorillas of the CB calculated to have been at 1.75 Ma (Scally et al. 2012). See Fig. 15.8a
	(7) 2.0 Ma: Separation of the Bangweulu and Lufubu drainage systems from the upper-western CR tributaries	(7) Founding of *Hydrocynus* "clade B", and "Clade C" diverges from "Clade D" and *H. vittatus ca.* 2.0 Ma (0.8–3.0 Ma) (Goodier et al. 2011)
	(8) 1.8 Ma: The Lufubu system is isolated from the Bangweulu river system and flows into Lake Tanganyika	(8a) Speciation of *Pseudocranilabrus* "lufubu" (1.4–2.3 Ma) (Koblmüller et al. 2008). (8b) Divergence of *Synodontis nigromaulata 2* from *S. nigromaculata3* (1.0–2.7 Ma) (Day et al. 2009)
	(9) 1.7 Ma: Major south to north flowing tributaries of the *Cuvette Central* region are in place i.e. Lomami River	(9) Two genetic markers of the guenons populations (*Cercopithecus lomamiensis* and *C. hamlyni)* have been estimated to be 1.7 Ma (3.2 Ma–0.5 Ma at 95 % confidence level) and 2.8 Ma (4.3 Ma–0.6 Ma at 95 % confidence). *C. lomamiensis* is separated from *C. hamlyni* by both the Congo and Lomami rivers (Hart et al. 2012). See Fig. 15.8b
	(10) 1.5 Ma: isolation of Lake Taganyika from the CRS, with consequent establishment of the Lukuga River outflow	(10a) Phylogenetic dating of the *Hydrocynus* population in Lake Tanganyika compared populations in the Bangweulu system (Goodier et al. 2011) (10b) Lukuga River appears to from a partial barrier between two chimpanzee population (see Fig. 15.8a)
	(11) 0.8 Ma: Establishment of the modern day Ogoué River sands (Seranne et al. 2008)	(11) Divergence date between southern and northern mandrills (Telfer et al. 2003). See Fig. 15.8b

15.5 The Evolution of the Congo Basin Drainage

Owing to the sensitivity of rivers to vertical tectonic displacements, and their ability to adjust to surface warping through changes in their channel, and subsequently their drainage pattern (Howard 1967; Holbrook and Schumm 1999), the CB rivers patterns provide insight into the evolution of the broader landsurface. Although the time response to change remains difficult to estimate, as it depends on rock strength, stream characteristics and the magnitude of tectonic activity (Holbrook and Schumm 1999; Leturmy et al. 2003; Lucazeau et al. 2003).

Major changes in the fluvial geomorphology of the CB occurred during the late Cenozoic (Table 15.3). Throughout the Neogene, the major rivers of the CRS began to develop their modern day forms. This change was driven by several factors, dominantly structural controls, tectonics and related autogenic fluvial processes. However this ongoing development was not uniform, as can be seen from 18 of the present day drainage patterns, indicating that the development of the CRS has been multi-phase and has several dominant controls.

The rivers of the eastern CB have been highly influenced by the geological young, and ongoing tectonic activity of the EARS, in particular its Western Branch (Fig. 15.7). While the geodynamic effects of the Western Branch have a limited spatial extent in the north-east of the CB, it is extensive in the south-east being and has resulted in the present contorted, trellis and modified rectangular-angulate and sub-dendritic drainages (Table 15.2; Figs. 15.3 and 15.7). These drainages are probably the second youngest of the CB drainages, having undergone significant re-organisation since the development of the EARS. The affects of the EARS on drainage in the region likely began in the Late Miocene with the formation of horst and graben structures, with increasing tectonic activity, including uplift, until the Pliocene-Pleistocene (Ring 2008; Bauer et al. 2010, 2012; Decrée et al. 2010; Roller et al. 2010). This multiple tectonic phases resulted in the contorted pattern of over the majority of the region (Figs. 15.3 and 15.7). This is evident in Fig. 15.6c, where vertical incision is dominant and the river channels in the region have eroded to similar elevations.

According to Pinet and Souriau (1988) there are two phases that characterise regional uplift: the initial 2.5 Myr phase involving constant denudation focused on the uplifted region, resulting in high sediment production and infilling of basin areas. The second phase occurs once the tectonic activity has ceased, with a 25 Myr period of weaker erosion occurring across a greater spatial extent leading to sediment movement throughout the greater basin (Pinet and Souriau 1988). Therefore, in the CB, the uplifting eastern basin margin is likely providing a large sediment supply that is transported westward by the eroding eastern rivers, and along with sediments transported by the northerly flowing rivers of the south CRS, accumulates in the central basin (Fig. 15.6a, b), where it undergoes reworking before being deposited offshore. This accumulation of poorly consolidated sediments has allowed the central drainages (*Cuvette central* and Western Congolain wetlands) to accommodate fluvial changes through horizontal re-working of the sediments. Thus the rivers of the central basin are more likely to have accommodated rejuvenation and adjustment than those on the Precambrian basement, as shown by their sub-dendritic to dendritic pattern. This development of a highly dynamic river network in the region is probably younger than the drainages of the eastern basin; serving as the regional interface between changes in the eastern and western drainages and changes in the CRS base level at the CR mouth. Thus the eastern and central drainages of the CB are likely to be Pliocene in age, with elements being inherited from Middle to Late Miocene.

The peripheral drainage patterns to the south, west and north of the central basin, are dominantly structurally controlled (the trellis drainages of southern Batéké, Sembe-Ouseso, Kwango Valley and mid-Congo; Table 15.2 and Fig. 15.3) and along with parallel drainage in the south (Lunagwe, Table 15.2 and Fig. 15.3) pre-date the central basin drainage (i.e. mid-Cenozoic to Mid-Miocene). This is not to say there have been no changes in these drainages systems but rather that the dominant drainage was already established by the Mid-Miocene.

Biotic evolutionary events provide important lines of evidence to constrain timing of major changes in location of river channels of the Congo drainage net. These include timing of formation of the present day CR and expansion and development of the drainage network. Comparison of river topology at regional scales reveals strong controls of the local geology, as indicated by the juxtaposed drainage patterns.

The south-to-north flowing rivers of the central basin region are likely to precede the east-to-west flowing rivers of the region; with the northerly flowing rivers being emplaced *ca*. 2 Ma. This is evidenced by genetic differences of the guenons and genetic variance of bonobos to the east and west of the Lomami River (Hart et al. 2012; Kawamoto et al. 2013; Table 15.3 and Fig. 15.8a, b). None of the east-to-west flowing rivers (apart from the CR) appear to have been a barrier to bonbos (Kawamoto et al. 2013), these rivers are therefore likely younger and/or of have not been continuously flowing for a sufficient time to form a true barrier. Similarly, it appears that only the north-to-south lower Oubangui River is a barrier dividing central and eastern chimpanzees, with easern chimpanzees moving across the east-to-west flowing rivers on the northern central basin

(Fig. 15.8a). Both these situations in the CB may be analogous to that seen in the east-to-west flowing Malagarasi River (Fig. 15.3) that forms an ephemeral barrier to chimpanzee dispersal (Piel et al. 2013). The smaller east-to-west flowing rivers of the central basin appear to form ephemeral barriers (if they form barriers at all) which suggests that these rivers are dynamic, changing both in size and location.

It is important to consider the relative roles of inheritance and rejuvenation, versus the origin of new features as interacting controls over the overall evolution of the basin. A better understanding of the development of the CRS will be achieved with the increasing merging of geomorphic, geologic (especially direct dates of prominent features, such as large waterfalls, e.g. the Lower Congo) and phylogenetic studies. It is through the combination of the fluvial evidence, data about the landforms over which they flow and the species they host (fishes) and impact (primates) that increasingly detailed and accurate picture of landscape evolution over the Neogene will be elucidated.

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