BIG RIVERS WORLDWIDE

Paul Edwin Potter and W. Kenneth Hamblin



Big Rivers of the World (cover)

Africa

- 1. Benue
- 2. Limpopo
- 3. Niger
- 4. Nile
- 5. Orange
- 6. Senegal
- 7. Zaire (Congo)
- 8. Zambezi

Australia

- 9. Cooper Creek
- 10. Murray-Darling

Eurasia

- 11. Amur
- 12. Bramhaputra (Tsangpo)
- 13. Chao Phraya
- 14. Danube
- 15. Don
- 16. Dnepr
- 17. Dnestr
- 18. Emba
- 19. Ganges
- 20. Godavari
- 21. Ili
- 22. Indigirka
- 23. Indus
- 24. Irrawaddy (Ayeyarwady)
- 25. Jordan
- 26. Kolyma
- 27. Krishna
- 28. Lena
- 29. Mekong

- 30. Ob
- 31. Po
- 32. Red (Hong)
- 33. Rhine
- 34. Rhone
- 35. Salween
- 36. Seine
- 37A & 37B Syr Darya and Amu Darya
- 38A & 38B Tigris-Euphrates
- 39. Ural
- 40. Volga
- 41. Yangtze (Changjiang)
- 42. Yellow (Hwang He)
- 43. Yenisey

The Americas

- Amazon (includes Amazonas, Solimões, & Marañón)
- 45. Colorado
- 46. Columbia
- 47. Fraser
- 48. Magdalena
- 49. Mackenzie
- 50. Mississippi
- 51. Missouri
- 52. Orinoco
- 53. Paraná
- 54. Paraguay
- 55. Rio Grande
- 56. São Francisco
- 57. Uruguay
- 58. Yukon

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Big Rivers Worldwide Part 1 Origins

By Paul Edwin Potter and W. Kenneth Hamblin

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Big Rivers Worldwide Part 1 Origins

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ABSTRACT

The geologic characteristics and origins of big river systems—35 in Eurasia, 15 in the Americas, eight in Africa, and two in Australia—are the result of plate tectonics, climate, volcanism and changes in relative base level. Collectively, these four, but mostly plate tectonics, determine the location, size, shape, and orientation of a large watershed, its longevity and most of its pattern since early in Earth history. Big river systems are, in broad terms, relatable to the Wilson Cycle of initial hot spot \rightarrow dome \rightarrow continental rift \rightarrow arm of the sea \rightarrow small ocean \rightarrow large ocean and passive margin \rightarrow small (closing) ocean with an active margin (ocean-continent or micro-continent or continent-continent convergence) \rightarrow new direction of continental tilt and drainage asymmetry. Thus, big river longevity, like global landscape evolution, operates on the same time scale as tectonic cycles.

We found the breakup of Gondwana and the closing of the Tethyan Ocean by many small microplates plus Africa, Arabia, and India to be responsible for most of the drainage pattern of Eurasia. The closing of the Tethyan Ocean created most of the mountain chains and basins of southern Eurasia from Spain to Vietnam, a distance of some 13,000 km. In Eurasia, the divide between north-flowing rivers and rivers flowing to the Pacific and Indian Oceans closely follows the northern limit of Gondwana. In North and South America, ocean-to-continent convergence and accretion of microcontinents to the Cordilleran and Andean orogens are responsible for much of the major drainage pattern of the Americas. A second important result is the number of these rivers that came into existence, essentially in their present form during the Miocene, even though a few have ancestors traceable back to the Carboniferous and perhaps even earlier.

The key to the long-term survival of a large river is location on a long-lived craton or passive margin and persistence of continental tilt, all without interruption by desertification, continental glaciation or volcanism. Conversely, orogenies both destroy existing big rivers and form new ones.

INTRODUCTION

Big river systems are an intergral and essential part of Earth dynamics. Examples of the role of big rivers in Earth dynamics include geomorphology at all scales, tectonics (erosion induced uplift and isostatic rebalancing of the crust), the filling of sedimentary basins (thick sandy and muddy fills, mixed terrigenous-carbonate fills, mostly carbonate fill or starved basins), and geologic history (giant alluvial fans/paleo Amazons) plus all the global geochemical cycles dependent upon the transfer of continental mass (solids and chemical compounds in solution) to the ocean. In addition, the big deltas and thick alluvial fills of big rivers are rich in petroleum and coal. Rivers, large and small, also play a role in plant and animal geography and have long been a key element in human affairs; for example, transportation, flooding and irrigation, political boundaries, and inspiration for writers, painters, and musicians.¹ Rivers go far back in time (Mojzsis et al., 2001; Wilde et al., 2001) and their

beginnings inspired Hadding (1929) to speculate about the first rains. So from many points of view, rivers, and especially big rivers, merit our full attention.

There is a vast, diverse literature about rivers and the search engine GEOREF alone has 31,183 entries about "rivers." Of these, however, only a tiny fraction are about big rivers and their geologic origins. We focused our efforts on two key questions, "What are the longterm geologic processes that control modern big river systems?" and "What is known about the longevity of modern rivers?" Answers to both questions should go far to improve our understanding of the great variability of rivers large and small (Schumm and Winkley, 1994, p.5). We hope these answers will also provide useful insights to those who work with more immediate human concerns such as flooding and irrigation, navigation, land use, power, river training and restoration, biology, and sedimentation as well as those who explore for petroleum and placer mineral deposits. Excluded from our discussion are short-term riverine dynamics and changes on the

¹ Riverine titles of music abound: think of Moonlight on the Wabash, the Blue Danube Waltz, and the tone poem the Moldau. And there is even a short symphonic piece by Tobias Picker in 1986 that totally captures the spirit of our efforts called Old and Lost Rivers!

scale of Pleistocene glacial-interglacial changes and their effects on river discharge and load, riverine morphology (braided vesus meandering), avulsion, etc. Nor do we consider the role of catastrophic floods. Instead we focus on the factors that have controlled big rivers through the long sweep of geologic time and use 60 modern rivers as our data base. These are scattered across the globe: 35 in Eurasia, 15 in the Americas, eight in Africa, and two in Australia (Fig. 1).

METHODS

We approached the origin of big river systems by combining an analysis of a widely scattered world literature in English, German, French, Spanish, Portuguese, Russian, and Chinese with study of world maps and imagery. The scant literature on the origin and evolution of big river systems contrasts with the vast flood of articles on the geography of rivers, their ecology, engineering problems (river training) and hydrology, geomorphology, and sedimentology. Literature relevant to the origin of big river systems is widely scattered and well concealed (Potter and Hamblin, Part 2, this volume) so much patience and persistence was required to find it. We used GEOREF and references collected from more than 25 years of joint interest in the origins of big river systems. The most useful papers were those that linked a river to 1) dateable offshore deposits at its mouth or in its lower alluvial valley, 2) a dateable structural feature in its watershed, and 3) to relevant paleogeography. Because explicit papers on the origin of rivers are relatively few, we often pieced together scattered, incomplete evidence and combined it with deductive logic. Two texts that discuss the geologic origins of big rivers are those of Summerfield (1991, Chapter 16) and Hamblin and Christiansen (2004, p. 331-335).

Simple as it may seem, organizing this literature into an annotated bibliography (Potter and Hamblin, Part 2 this volume) was an important step forward. General or process papers (on plate tectonics, basin formation, geomorphology, etc.) were grouped together to form one part of this research bibliography followed by specific studies of modern rivers in Africa, Australia, Eurasia, and the Americas. This effort went far to lead us to the conclusions that follow. From this large bibliography we selected 60 modern rivers, mostly but not all large ones, whose essential characteristics are summarized in Appendix 1 (p. 41) of Part 1. We also collected some studies of ancient river systems identified in basin studies, which added an important dimension to our results. In addition, our search of the literature identified some 23 papers that demonstrate that the study of big river systems, although always outside the main themes of geology, has indeed had a long history (Table 1).

We used satellite imagery, geologic maps, colored digital shaded-relief maps, and radar imagery to study details of river patterns and their relation to watersheds and landforms. This "field work" helped us to generate ideas and better evaluate the literature. The present availability of such maps for Russia and China, which collectively cover about 31 percent of the Earth's land surface excluding Antarctica, added much.

Most of the data about river length, watershed area, and discharge used in our paper come from Allen (1997, Table 3.4). For the spelling of foreign place and river names, we followed those used in the 1992 edition of the *Oxford Atlas of the World*.

DRAINAGE AND TECTONICS

As we progressed with our study, we developed six tenets about big river systems that we think go far to explain their development (Table 2). We place these early in the text so the reader can evaluate their validity against the examples summarized in the Appendix and discussed in the text. Almost all of these are related to plate tectonics.

Six aspects of tectonics (Table 3) underpin the tenets of Table 2. These range from converging or diverging plates to local faulting, folding, and tilting within large or small watersheds. Tectonics, for example, determines the major relief of a watershed (the location of its highlands and lowlands and their elevations), the shape and orientation of the watershed, the river pattern within that watershed and its persistence. On a smaller scale Melton (1959) suggested that 25 to 75 percent of the unglaciated streams of the North American craton were relatable to adjustment to local structure. It seems likely to us that for big rivers there is an even greater role for tectonics. Hence, we start with tectonics and illustrate its role using examples from around the world. Earlier papers that either totally or partially addressed these questions on continental and subcontinental scales include those of Timofeov (1965), Inman and Nordstrom (1971), Dewey and Burke (1973), Audley-Charles et al. (1977), Potter (1978), Dickinson (1988), Frostick and Read (1989), and Summerfield (1991). Papers of special note on watersheds include those by Glock (1931), Miall (1981), Holbrook and Schumm (1999), and Schumm et al. (2000). Free use of their contributions and those of others is made below.

The Wilson cycle of initial hot spot \rightarrow dome \rightarrow continental rift \rightarrow arm of the sea \rightarrow small, opening ocean \rightarrow large ocean with passive margins \rightarrow small closing ocean with active margin (ocean-continent, microcontinent-continent or continent-continent) \rightarrow new direction of continential tilt and drainage asymmetry underlies all the large-scale aspects of big river drainage. Examples of such tectonic control, starting with plate convergence, are drawn from all the continents except Antarctica.

Plate Convergence: This is the most important single factor in continental drainage, because its influence on big rivers extends far beyond the area of deformation. There are two distinct consequences: *near field drainage* within the orogen and the *far field effect* of collision on tilt. Orogenic drainage in areas of plate convergence with an oceanic plate has a strong linearity parallel or subparallel to coastline—long river segments parallel to tectonic strike connected by short segments at right angles draining to the sea parallel to direction of tectonic transport. Such trellis drainage commonly extends for hundreds of kilometers along strike for either an oceanic continent or a sutured continent-continent collision (strike-parallel rivers follow megashears produced by obliquely colliding plates).

Examples of strike-parallel drainage within orogens in the Americas include the Yukon, Fraser, Columbia, and the Magdalena Rivers in the Americas and in Southeast Asia the upper reaches of the Mekong, Bramhaputra, and Yangtze. Far field effects are also two fold. Oceancontinent collisions reverse tilt toward the trailing margin inboard and in front of the orogen (the Americas), whereas continent-continent collisions produce tilt in opposite directions away from the resultant highlands formed by the suture (Asia). Thus, when a passive continental margin is impacted by either an oceanic or continental plate, the old river systems of the passive margin are destroyed and replaced by new ones (continental back tilting). Below are examples from the Americas.

In the Americas, there is drainage eastward across both continents toward the passive margins of the Atlantic and Arctic Oceans (Fig. 2), because of oceancontinent convergence along western South America and a combination of microplate accretion and convergence in North America. Thus, both Americas provide ideal models of continent-wide tilt away from convergent margins with strong continental asymmetry of drainage. In North America, Cretaceous and Tertiary orogenies (ancestral Rockies) produced tilt to the east, northeast, and southeast reversing earlier tilt to the west and southwest in response to the Appalachian Orogeny (Dickinson, 1988, Fig. 1.8). In South America the reversal of the lower course of the Amazon occurred during the Middle Miocene (Hoorn, 1994) as the Andean chain rose. Like the longevity of cratonic basins and arches, continental tilt can persist on the order of several hundred or more million years, dependent upon marginal continental collisions or interruption by East African-style intracontinental uplift and rifting. Thus, persistence of continental tilt is one of the limiting factors for the maximum age of a big river system.

There are two other consequences of plate convergence for large river systems-foreland basins and megashears (see Shears and Megashears). Foreland basins develop where thrust stacking of the impinging plate has depressed the crust of the former passive margin. The relative rate of supply versus subsidence of this basin-is it overfilled or underfilled (Flemings and Jordan, 1989)-determines the orientation of drainage near the mountain front. If underfilled, the river will flow parallel to the strike of the orogen basin (or may be occupied by either a shallow or deep arm of the sea). The lower courses of Lena and Aldan (Fig. 3), the Ganges, the upper Danube, and the Tigris and Euphrates are all good examples of rivers in under filled foreland basins that flow parallel to the tectonic front of the orogen, whereas the Marañón, Madre de Dios, and Beni all in Peru and Bolivia are good examples of modern overfilled basins each with a river flowing perpendicular to the front and down continental slope to the sea. An ancient example of a basin that has alternated between over- and underfilled through time is the Appalachian Basin.

Eurasia illustrates continent-to-continent suturing on a grand scale (Fig. 4). From a global perspective, because Eurasia forms about 42 percent of the six continents presently lacking continental glaciation, the closing



Figure 1. Rivers studied, 60 in all. See appendix for names, lengths, probable ages, and summary remarks.



Table 1: Landmark Steps in the Geological Study of Big River Systems

Spencer, 1890

Uses bathymetry of the Great Lakes and subsurface geology to infer the headwaters of the ancestral St. Lawrence River before Pleistocene glaciations

Gilligan, 1920

Envisions a river system extending into Scandinavia for the Millstone Grit of Great Britain

Weller, 1927

Suggests that the Mississippian Chesterian sandstones of the Illinois Basin were brought to it by a large river sourced far to the northeast

Blackwelder, 1934

A literature review of the origin of the Colorado River going back to 1861; recognizes its complex origin of superposition, antecedence, and possible overflow from a wet to a dry basin

Barbour, 1936

An amazing study of the origin of the Yangtze River far, far ahead of its time

King, 1967

Discusses the importance of dating erosion surfaces and, by implication, rivers, using their offshore record; a landmark step that he first published as early as 1958

Mann and Thomas, 1968

Traces the Mississippi River back to the Late Paleozoic and the first to carefully define the age of a river: "The time of origin of a river drainage system is defined as the earliest date at which a persistent stream occupied a valley" (p. 187)

Korzhev, 1970

Maps major divides of the Earth, recognizing continental drainage to Arctic, Atlantic, Indian, and Pacific Oceans (plus internal drainage) and calls attention to the principal divide of Eurasia and Africa that extends from Angola into northern Siberia, which varies greatly in age, width, and elevation. Important background paper for analyzing drainage systems of supercontinents

De Rezende, 1972

The first to think continent-wide about rivers and megafractures

Burke and Dewey, 1973

Plate tectonic pioneers relate great rivers and paleoslopes to triple junctions and continental collisions

McMillan, 1973

Large Tertiary river system extends from the central Canadian Rockies to the Tertiary basin between Greenland and Labrador. Beautiful synthesis much ahead of its time

Miall, 1981

Pioneering paper illustrates drainage in 12 plate tectonic settings

Potter, 1978

General overview of big river systems from a global perspective

Miall, 1981

Pioneering paper illustrates drainage in 12 plate tectonic settings

Winker, 1982

Shifting areas and locations of onshore drainage watersheds inferred for different Tertiary depositional centers of the Gulf Coastal Basin

Dingle and Hendey, 1984

Offshore Mesozoic and Tertiary deposits related to two onshore drainage changes of the Orange River in South Africa; they suggest that these captures occurred during lowstands when steeper gradients caused faster headward erosion

Poag and Sevon, 1989

Systematic reconstruction of the denudation history of the central Appalachians from 23 isopach maps of coastal plain and continental shelf deposits

Lindsay et al., 1991

India-Asia collision, and thus the history of the Ganges-Brahmaputra Rivers, is tracked by a sequence-stratigraphic interpretation of their deltaic deposits (spectacular verification of King's suggestion that the history of ancient river systems is recorded in their preserved offshore deposits)

Ollier, 1991

Argues that when a tectonic obstacle forms across a large river, the river will form an antecedent gorge and that reversal only occurs by backtilting

Archer and Greb, 1995

Infer a "paleo Amazon" for large Carboniferous river system in eastern North America

Ollier, 1997

Argues that some rivers may be older than the mountains they cross, that totally new drainage is unlikely on passive margins, and that the ages of some rivers may rival the ages of the major features of global tectonics; all important new ideas, well argued

Potter, 1997

First effort to establish the drainage history of an entire continent for a large interval of Phanerozoic history; estimates the pre-Miocene extent of the Amazon's watershed

Brookfield, 1998

Rivers of southern Asia from the Caspian Sea into Pakistan, India, Myanmar (Burma), China, and Indochina explained in terms of the great sweep of the India-Asia collision starting in the Paleocene

Grosswald, 1998

Overview of spectacular drainage changes in northern Eurasia since the last Weichselian ice sheet provides important model for Carboniferous and earlier glaciations

Table 2: Fundamental Tenets of Rivers

1. As long as the Earth's hydraulic system has existed, rivers have followed depressions formed by tectonics (and loading) on their way to base level (lowest potential energy).

2. Big river systems are sensitive to slow changes in tilting, subsidence, and uplift, but respond almost instantly in geologic terms to changes in rainfall, discharge, and to faulting.

3. Drainage patterns evolve by headward erosion, stream capture, downdip extension (or updip retraction during marine invasion), and by continuous adjustment to differential (and commonly subtle) subsidence within their watersheds.

4. The size and shape of a large river system is determined by the tectonic history of its watershed (wide craton versus tightly sutured, accreted block, for example) and its base-level history.

5. Most rivers have different segments that may range in age from as old as Jurassic to Late Cenozoic to Pleistocene.

6. The age of a river system depends not only on its tectonic history, but also on accidents such as desertification, continental glaciation, and volcanism, any of which, in the extreme, can greatly or totally alter or destroy a river.

of most of the Tethyan Ocean with the formation of highlands from the Atlantic to the South China Sea is the dominant control on today's river drainage.

Eurasia's drainage is controlled by two megasutures both extending from one end of Eurasia to the other. The paleo-Gondwana suture dates from the Late Permian, when segments of Gondwana started to impact Eurasia and the other dates from the Paleocene when first India impacted Eurasia followed by Africa and Arabia in the Miocene. North of the Gondwana suture identified by Smith (1999, Fig. 2), drainage is to the Atlantic (Seine, Rhine, and Vistula) and to the Arctic Oceans (Ob, Yenisy, Lena, Indigirka, and Kolyma); on its east side, to the Pacific (Amur, Yellow, Yangtze, Red, and Mekong); and on the south side of the suture, to the Indian Ocean (Ganges–Brahmaputra, Indus, Irrawaddy, Salween, and Tigris–Euphrates Rivers). In addition, three small rivers (the Syr Darya, Amu Darya, and Chi in southern Kazakhstan) flow to the northwest toward the inland Aral Sea, and the Ili flows into Lake Balkash. From the above perspective of north-flowing Eurasian drainage away from the Gondwana suture, there are two exceptions: first, the south-flowing drainage of the Don, Dnestr, Dnepr, Volga, Ural, and Embu Rivers into the Black and Caspian Seas and, secondly, the Amur River, which is north of the paleo-Gondwana suture, but flows into the Pacific (Fig. 4). We interpret these south-flowing rivers as relic drainage to the former passive margin of the north side of the Tethyan Ocean. See Kheirov and Khalilov (1990) for evidence that the Volga supplied sediment to the Caspian in the Paleocene, and see Görör (1989) for evidence that the Black Sea started in the Jurassic, when its northern shores dipped to the south as a passive margin. Thus, the collective watershed of all six south-flowing rivers of southern Russia appears to be quite old and gives a glimpse of some of the southerly drainage of northwestern Eurasia before the Tethyan Ocean was closed. The Danube also drains to the Black Sea, but has its headwaters in a Miocene foreland basin and drains across the Pannonian Basin of Hungary (also of Miocene-Pliocene age) before crossing the Transylvanian Mountains to enter the Black Sea along a tectonic low (Neppel et al., 1999).

Northern Australia and New Guinea provide a present-day example of convergence in its early stages (a small ocean separates a large plate from a migrating orogenic belt), and Uzbekistan, Turkmenistan, and southern Kazakhstan provide an example of drainage and topography after collision (Fig. 5). The impact of the northward-moving Australian Plate against the Pacific Plate has created the Miocene mountains of New Guinea and a small foreland basin bordering the shallow Arafura Sea (underlain by continental crust) to its south. Continued convergence will close the Arafura Sea and backtilt northern Australia. Uzbekistan, Turkmenistan, and southern Kazakhstan show us what northern Australia might well be like after it converges with New Guinea. In these three countries the former Tethyan Ocean exists only as small inland seas and lakes and is infilled from the south by a series of foreland basins with oblique drainage to the northwest.

In sum, major reorientation or reversal of continental tilt is the consequence of a converging oceanic or continental plate impacting a passive margin.

Table 3: Tectonic Controls on Rivers

Plate convergence

Ocean-continent and microcontinent-continent: Forms marginal mountain belts with volcanism plus tilt and asymmetry of drainage away from collisional side

Continent-continent: Forms large interior, ovalshaped highlands at suture of supercontinent, with mostly centripetal drainage. Repeated impacts of multiple microcontinents have similar effects

Plate separation (extension)

Starts with doming, triple junctions, and continental-scale rifting passing first to small then large intervening oceans, with some coasts bounded by long, high coastal escarpments that divert much drainage inland; major rivers likely to be localized by aulacogens and rifts along such passive margins

Regional tilting

Causes lateral migration (when tilt is away from stream course); backtilting (initial ponding and stream reversal) occurs when tilt is toward headwaters, and accelerated erosion when tilt is toward mouth

Domes and doming

Create radial drainage on shields and cratons and vary greatly in origin and size

Basins and arches

Basins of all types localize both mouths (deltas) and important interior segments of large rivers (may alter alluvial facies as well, (if differential subsidence is sufficient), and regional arches may deflect streams. Small anticlines and synclines are both likely to influence river course, especially where river crosses flanks (migration down-plunge)

Shears and megashears

No unique origin, but all represent major translation; when young and active, have linear relief and surface expression of active horsts, grabens, and pull-apart basins, but when old, likely to localize large, coastal deltas and elongate, intracratonic sag basins

Smaller faults and folds (10 to 100 km)

Locally may tilt a short segment of a river valley, causing lateral migration, ponding, or entrenchment. Always favor erosion through enhanced fracture density and permeability, both of which promote river capture

Basement grain

Sum of all of the above controls, including differential resistance of bedrock to erosion Upon impact, the continental shelf of the passive margin is consumed, so that Andean or Himalayan highlands replace the original coastal plain, continental tilt is reversed (Fig. 2), and most drainage is now away from the orogen (as in the Americas) or radial from the suture (as in much of Asia). This sequence of events effectively destroys the original passive margin drainage and replaces it with a new continental drainage flowing in the opposite directions.

Plate Separation: Continental rifting is perhaps the best the understood of all the plate tectonic controls on big river systems. The underlying mechanism is initiation of a hot spot \rightarrow dome \rightarrow cooling \rightarrow collapse of dome with rifting \rightarrow invasion of the sea \rightarrow coastal



Figure 2. Asymmetrical drainage of the Americas. Included in Pacific drainage are some areas of internal drainage in both North and South America.



Figure 3. Under- and overfilled basins: (A) Underfilled foreland basin in front of the Verhoyansk Orogen in Siberia (after Exxon, 1985 panels 5 and 6). Here much of the lower courses of the Lena and Aldan Rivers closely follow the depressed crust in front of the structural front, whereas the Vilyuy joins the Lena at a structural bend of the orogen (extension at bend creates additional subsidence in front of orogen). (B) and (C) Overfilled foreland basins (light gray) in front of the Andes in Bolivia, where the Madre de Dios and Beni Rivers flow perpendicular to the Andean structural front (after Exxon, 1985, panel 14).

escarpment with inward drainage away from the seacoast. Much later a buried old and cold rift, the failed arm of a triple junction formed by a dome, may localize a large river draining to the coast through its continued weak subsidence (Burke and Dewey, 1973, Fig. 2).

The coasts and drainage of South America and Africa illustrates well how regional, continental-scale drainage on two now far-separated continents has a common heritage traceable to early doming and rifting an important observation made initially by Dewey and Burke (1973) and elaborated by Cox (1989) and Moore and Blenkinsop (2002). Four highlands with cores of older rocks believed to represent former plume-headrelated hot spots are in part associated with Cretaceous and later rifts, both perpendicular and parallel to present coasts (Fig. 6). Although initial rift shoulders are long vanished, descendent high escarpments in southern Africa, southeastern Brazil, and the interior highlands of the Guyanas and Guinea divert drainage long distances inland from the coast, as is true of eastern Australia, peninsular



Figure 4. Drainage of Eurasia: Gondwanan rocks in light gray (After Smith, 1999, Fig. 2) and present Atlas-Alpine-Zagros-Himalayan suture (after Exxon, 1985 panels 9, 10, 11 and 12). Also shown are two areas of special interest – relic Tethyan drainage (rivers 5, 6, 7, 8, 29 and 30) and the watershed of the Amur River (1).

India, Norway, and Labrador. The highlands of the Gran Sabana in Venezuela and Guyana in South America and their equivalent in Guinea in Africa, the Fouta Djalon Highland, are examples of domes with pronounced topographic expression, both linked to the separation of South America from Africa (Fig. 6). In addition, large rivers such as the Amazon, Niger, and Paraná-Uruguay have mouths near or above Cretaceous rifts, as do several smaller Argentine rivers crossing Patagonia today. Other examples of coastal rifting localizing river deltas include the Rhine and the Zambezi. Because continental separation has occurred on almost all sides of Africa and Australia, both continents have rivers that start and end on passive margins (the Murray-Darling and the Orange). Earlier, both Audley-Charles et al. (1977) and Dickinson (1988, Fig. 1.6), recognized African drainage as a special type dominated by rifted highlands and passive margins. Could it be that, with comparable rainfall and no giant rift system in Africa, the two continents might earlier have had closely similar continent-wide drainage?

The Red Sea, southern Africa, southern Brazil, Norway and the coast of Labrador all provide good examples of continental and subcontinental extension in all stages from initial doming to final passive margins (Fig. 7). Collectively, these show a clear sequence from the present East African Rift System \rightarrow Red Sea \rightarrow high coastal escarpments (southern Africa, eastern Australia, Labrador, and southeastern Brazil) \rightarrow high plateaus near coast (Pakarima Mountains in the Guyanas and Fouta Djalon Highland in Guinea) \rightarrow ultimately to passive margins with thick coastal plain wedges sourced by large rivers (Gulf Coast/Mississippi and Niger delta).

Young rifts with high heat flow and shoulders disrupt drainage and either reverse drainage or divert it away from the rift zone, whereas old, cold rifts localize rivers through weak, long-term subsidence. The domes associated with this process are long-lived, are commonly reactivated, and thus influence rivers long after initiation. Smaller domes, on the other hand, may simply have cores of older rocks, low or no escarpments, and very subtle topographic expression. As a structural dome or weak high develops, a superimposed river may become entrenched in a valley or canyon across it, but more likely will follow a topographic low around it, as is true for the Orinoco River in northeastern South America (Fig. 8).

Structural domes with radial or diverted drainage range in size from tens to hundreds of kilometers in diameter and have different origins ranging from hot spots to forebulges. Domes vary from almost circular to elliptical in shape and, as they become more elongated, may pass into regional arches. On cratons, domes have great longevity and may have selective times of activity when they influence river systems and sedimentation. The Angara Shield of Siberia, the Black Hills and Ozark Dome of United States and the Guyana Shield of northeastern South America are good examples of domes with radial drainage.

Basins and Arches: Cratons and their passive margins, typically have broad, low regional arches separated by sag basins, both of which affect big river location in the absence of a new, different continental tilt, faulting, glaciation, and desertification. Modern examples of rivers following a regional structural low include the Rhine and Rhone Rivers, both of which follow Miocene grabens throughout much of their courses. Similarly, the lower Mississippi closely follows the axis of the Cretaceous Mississippi Embayment, which overlies a Neoproterozoic aulacogen. In the nearby Illinois Basin to the north, Mississippian Chesterian deltaic and fluvial sandstones parallel and are thickest above the southwesttrending axis of the the same underlying Neoproterozoic aulacogen and thinnest and least abundant along the flanks of the bounding arches of the basin (Fig. 9). The size of such arches varies widely from as small as 50 km in length to as long as 500 to 1,000 km. The larger of these regional arches seem to be the response to the orientation and intensity of marginal plate collisions, the forebulges of Beaumont et al. (1987). Although long-lived, the activity of regional arches depends upon the orientation of both the arch and the stress field, as is true for smallerscale faulting of 10 to 100 km or more in length. Once established, basins and arches on cratons are long-lived and repeatedly influence both the location of rivers and the pattern of marine invasions, both of which broadly follow basin axes. Rivers are prone to cross such arches at high angles rather than obliquely.

Shears and Megashears: These occur where plates

and microcontinents collide obliquely, have lateral displacements of tens to hundreds of kilometers, are common in accretionary terrains, and cause faulting and fracturing of bedrock at all scales. Such fractures create a complex topography of sag basins and half-grabens separated by pressure ridges, all of which localize major rivers. Because the resulting fractured rock facilitates headward erosion, strong linear river patterns result.

The Jordan River of the Near East in a semi-arid climate (Fig.10) and the Red River between Vietnam and China in a wet climate are two contemporary examples of rivers following megashears. The Dead Sea Transform, passing through Syria, Israel, and Jordan (formed as the Arabian Plate impacted the Mediterranean Plate) is over 1,100 km long and only flooded at its south end. The Jordan River, only 322 km in length, begins in the mountains of Syria and flows southward closely following the transform only a short distance, because of insufficient rainfall. On the other side of Eurasia, east of the Indian Plate, rivers such as the Salween, Irrawaddy, Mekong, and Yangtze follow curving right-lateral shears in their upper reaches (Brookfield, 1998, Fig. 8) and the Red closely follows a straight megashear almost 1,200 km long. The coincidence between the megashear and course of the Red River is almost total (Wang et al., 1998). One tiny and the other sizable, the exceptionally straight courses of the Red and Jordan rivers are the result of Gondwana impacting Asia as are the curving right-lateral shears of the upper reaches of the Salween, Irrawaddy, Mekong, and Yangtze (Brookfield, 1998, Fig. 8).

In the Americas, shear zone boundaries in accretionary terranes are widespread in Canada and Alaska, and some form valleys hundreds of kilometers long, such as the Rocky Mountain Trench of Canada. Without mountain glaciation these long linear valleys might well have an integrated drainage system similar to that of the Tsangpo (Yarlung Zangho Jiang) River of Tibet, which flows for 1,200 km along a suture formed by the India-Asia collision. The Yukon River (Fig. 11) closely follows two major right-lateral faults: the Kaltag Fault, trending generally to the northeast; and the Tintina Fault, trending to the southeast for a total of some 1,300 km (Exxon, 1985, panel 1).

In sum, it is the *structural grain* of the watershed of a river at any scale—the trend, kinds, and activity of underlying structures large or small in a river basin plus



Figure 6. Inferred hot spots (stippled) under present highlands and their subradial drainage in adjacent parts of southern South America and Africa (Cox, 1989).



After Cox (1989, Figs. 3, 4 & 5)

the differential resistance of its bedrock to erosion-that creates contemporary topographic lows in its watershed. Structural grain includes the distinctive drainage fabric of collisional margins, failed arms of buried aulacogens, domes and intra-continental rift systems, shears and megashears, crustal fractures, and basins and arches on cratons and passive margins. Most of these controls are long term, such as continental tilt, an old Precambrian shield or cratonic basins. Exceptionally, however, intense plate convergence as in Southeast Asia, may change local structure in only a few million years. Glaciation and desertification, both the result of climate change are, on the other hand, insantaneous as is volcanism. Comparison of the lower Mississippi and middle Rhine show well the difference between short-term climatic effects and long-term tectonic controls. For both rivers Pleistocene climatic changes greatly altered morphology and ratio of load to discharge, but their location never changed (axis of Mississippi Embayment and Miocene graben system). Desertification and volcanism also can both alter and destroy rivers. In unglaciated areas, the details of drainage patterns are delicately adjusted to underlying structure and bedrock (Melton, 1959). This is largely because of the universal tendency of rivers to follow structural lows and local zones of weaknesses, a tendency that explains many of their small-scale deviations from general trends. As important as this is locally, such deviations normally play only a small role. *Tectonics at all scales, from short fractures to long megashears to continental convergence is the fundamental control on big river evolution and pattern.*

SPECIAL EVENTS IN BIG RIVER EVOLUTION

Although all rivers undergo slow, continuous changes (and some perhaps even the rare catastrophic flood), most big, long-lasting rivers undergo one or even all three of the following special events in their history (Table 4): diversions, formation of lakes during times of change, and resurfacing (marine invasions, glaciation, desertification and even volcanism).

River Diversion: Included here are capture, deflection around a rising structure, bisection, and avulsion into a newly developing tectonic low, any and all of which can result from a marginal continental collision or perhaps migration over a mantle plume. Excluded here are the short-term avulsion processes of a large alluvial river, meander migration, etc.



Figure 7. Drainage evolution and rifting starting from the Ethiopian Highlands and Red Sea (young rifts, high heat flow, and high shoulders) to the passive margins of South America and Africa (both old rifted margins with low heat flow and with drainage diverted inland away from coastlines by escarpments). The mouths of the Niger, Benue, and Paraná-Uruguay are localized by Cretaceous rifts (aulacogens). The Orange River is notable, because both its headwaters and mouth are on passive margins, as are the headwaters and mouth of the Murray-Darling in southeastern Australia and the Paraná and Uruguay in Brazil.



Figure 8. Much of the Orinoco River of northeastern South America follows the contact between Precambrian rocks of the Guyana Shield and the Tertiary Llanos (molasse) Basin derived from Miocene uplift of the Andes (after Stallard et al., 1990, Fig. 1). Here the upper Orinoco, and rivers such as the Veniuari and Paraqua, may be as old as Jurassic, whereas rivers such as the Guaviare, Meta, and Apure are of Miocene age. Note also how the central highlands of the Guyana Shield causes the upper Orinoco and Veniuari to "take the long way" to the sea along the boundary of the Guyana Shield.

River diversion occurs by capture, by change in continental tilt via a new marginal orogenic belt, by block faulting, possibly a rising arch, by rifting, or by development of a new nearby basin. In addition, river diversion may be caused by continental glaciation or even possibly by widespread flood basalts and sand seas as discharge decreases. The time span of such events is wide ranging, from possibly 10 to 30 Ma or more years for reversal of continental tilt to less than a million years for arches or basins in active margins. It seems that many of these changes occur in a series of steps, some of which create temporary lakes or swamps. Of the three, capture by headward erosion is by far the most common, and may be the result of more rapid erosion through weak or fractured rock, differential distance to base level (differential gradients), or even asymmetry of rainfall on opposite sides of a mountain range. The rivers of Southeast Asia probably illustrate best big-river capture on a grand scale. Here in the great east bend of the Himalayas many river captures and reversals have been inferred as the result of accelerated deformation in the Miocene. Abandoned cols with fluvial sediment, intercepted drainage and barbed tributaries all point to a pre-deformation, large, single, south-flowing river comparable to the Mississippi (Brookfield, 1998; Clark et al. 2004).

Can a rising structure divert or even bisect a river? A few examples of this are reported. In France, a Lower Eocene (Ypresian) river almost 200 km long is inferred to have been bisected by a rising anticline with an abandoned col (Godard et al., 1994). Another example comes from the Lake Baikal region of southern Siberia, where the Lena lost its connection to the lake as a rift shoulder rose leaving a wide dry valley (Velichko and Spasskaya, 2003, p.47). In southern Africa, Bootsman (1997) illustrates diversion by faulting of the proto-Molopo system. Backtilting and diversion by rifting and rise of regional arches (swells and arches) in southern Africa is also shown by Pritchard (1979) and by Moore



Upper Mississippian, 320 Ma

Figure 9. Basin and Mississippi Embayments. The deltaic system of the Mississippian River of Swann (1963) brought sand and mud to the basin with most of it deposited along the basin's southwesternly trending axis. Trend of underlying Neoproterozoic aulacogen controlled development of both Illinois Basin and Mesozoic Mississippi Embayment. Thicknesses in feet.

and Larken (2001). Here salt pans, swamps, and lakes mark the termination of several small headwaters streams. Whether antecedence occurs and a gorge or canyon is cut across a rising structure or diversion or bisection occurs, depends on rate of uplift, neighboring topography, river discharge (low rainfall) and the possibility of capture.

Subsidence also diverts rivers into topographic lows, forming swamps or lakes. This subsidence may be a down-dropped fault block, central graben of a rift system, or an aulacogen—the failed arm of a large rift system (Burke and Dewey, 1973).

Role of Lakes: Lakes commonly occur at either the inception of a river or during its destruction, and thus are short-lived, but still have an important function for understanding big rivers. At least five different geologic situations show the importance of lakes to river evolution.

Lakes of foreland basins are perhaps the most common.

Such lakes form in the depression between the thrust stack of an orogen and the stable block in front of it as the sea withdraws. These lakes, filled by lacustrine deltaic mud and sands as well as carbonates and evaporites, may be either flooded again by the sea, overflow, or dry up if the climate is arid. Overfilling and desiccation both create a new land surface for river extension. Other possibilities are inland seas and lakes such as the Caspian and Aral Seas and Lake Balkash in central Eurasia, all three being the last vestiges of the closing of the Tethyan Ocean trapped between the converging continental plates of Gondwana and Laurentia. Finally, when such lakes and small seas cease to exist, a subaerial foreland basin with an integrated drainage system flowing to the sea develops. When sediment supply exceeds subsidence, drainage in front of the orogenic highlands is perpendicular to the suture (overfilled basin), but when subsidence is greater than supply, drainage parallels the



Figure 10. A"linear" tectonically constrained river: active Dead Sea transform fault and its control on the Gulf of Aqabah, Dead Sea, and Jordan River only 322 km long (Exxon, 1985, panel 10).

tectonic front (underfilled basin), and with even more subsidence the basin is flooded again by the sea (Flemings and Jordan, 1989).

Lakes are also common in youthful rifts and may be connected (wet climate) or isolated (dry climate). Examples of both occur in the rift valleys of Africa and in the Basin and Range Province of North America (Dickinson et al., 1988). The lakes of a large rift system and those of a major orogen disappear in different ways. As a rift cools and its shoulders lose their relief, early lakes fill and disappear and may eventually be followed by through-flowing drainage localized by a deeply buried graben. Examples include the Rhine (Andres, 1989), Rhone (Sissingh, 1998), and upper part of the Rio Grande River in the United States (Eaton, 1987). During the Laramide Orogeny in the central Rocky Mountains region of the United States, basins developed within its main trend and near its eastern limit, where they were ponded. These ponded basins, some quite large, have lasted as long as 4 to 6 Ma. When these structurally formed, ponded basins were finally filled, some drained to the Pacific and others to the Gulf of Mexico (Dickinson et al., 1988), thus becoming the remote ancestors of much modern drainage.

Lakes and swamps also occur where a river system is backtilted, as when a passive margin is impinged by a subducting, young oceanic plate; this appears to have happened to the Amazon in the Middle Miocene (Hoorn, 1994). In semi-arid regions, a previously through-flowing river may terminate in seasonal wetlands, swamps or even saline lakes as rainfall decreases, as illustrated by

Table 4: Processes and Consequences of RiverDiversion

Tectonic Diversions — Range from change in continental tilt (passive margin →convergent margin), deep crustal shears, rising or sinking fault blocks, rifting, and rising arches. Many river captures are the consequence of such tectonic events.

Resurfacing — Original drainage destroyed by marine invasion, continental glaciation, and less commonly, widespread volcanism or sand seas (desiccation).

Formation of Lakes — Usually occur during times of change (backtilting, tectonic diversions, glaciation, desertification, or volcanism).

the Okavango Swamp (Moore and Larkin, 2001), Lake Chad, the Sud Swamp of the middle Nile in Africa, and the paleodrainage of the Gobi Desert in Central Asia and western Australia. There are also many excellent examples in Australia described by Van de Graff et al. (1977), who mapped paleodrainage over most of Western Australia. Such paleodrainage is established by connecting topographic lows between now-separated linear playa lakes locally called "billabongs."

Volcanism, both local and regional, disrupts earlier drainage and forms lava dams and temporary lakes, which overflow, creating a new river course. Three examples are the Snake River in Idaho (Lupher and Warren, 1942), the Columbia (Tolan et al., 1984), and the Tiber in Italy (Alvarez, 1973). In addition, the pyroclastic and volcanic cones of convergent plate margins create complex systems of ephemeral lakes and drainage in the headwaters of many rivers, and, along with the regional volcanism associated with doming and early rifting, provide present-day models for the early Earth.

Numerous lakes, large and small, are formed by continental glaciation: some occupy large scoured depressions, many are local (behind morainic dams), and some are proglacial lakes beyond the ice front (Teller, 1995; Grosswald, 1998). Glacial lakes are most common where an ice sheet retreated in the same direction as regional slope, whereas retreat upslope deposits a valley train, with streams draining away from the ice front. Main-stream aggradation raises the local base levels of tributaries to form small deltas and glacial lakes in their mouths. This also occurs where a large, rapidly aggrading river such as the Amazon crosses a low-relief craton. Here, debris from the Miocene uplift of the Andes raised base level downstream across the continent in response to rising post-Wisconsin sea levels.

Resurfacing: At any stage in its history, a river may have its length or location altered by marine flooding, continental glaciation, deposition of widespread plateau basalts (or ash), or desertification and deposition of thick dune sands, all of which bury or destroy the earlier drainage network of the watershed, forming a new surface and new drainage (Potter, 1978, p. 25–26). Alvarez (1973), for example, described how the course of the Tiber River near Rome was changed by an outpouring of tuffs in the Middle Pleistocene. Lupher and Warren (1942) reported on the diversions of the Snake



After Exxon (1985, Panel 1) and Yorath (1991, Fig. 9.34)

Figure 11. Structural control of large segments of the Yukon River and its tributaries by the right-slip Kaltag, Porcupine, and Teslin Faults in Alaska and the Yukon Territories. The Yukon system occupies the topographic low between the Rocky and Pacific Mountain Systems (After Exxon, 1985 panels 1 and 7 and Yorath, 1992, Fig. 9.34). Miocene glaciation in the Pacific Mountain System is believed to have diverted the headwaters of the Yukon from the Pacific Ocean into its much longer present course into the Bering Sea.

River caused by volcanism in western United States. On a much larger scale, volcanism must have been especially important in the early Earth, much as it seems to have been on Venus and perhaps Mars, where the term "resurfacing" was introduced for this process (Strom et al., 1994, p. 10,923–10,924). Widespread continental glaciation provides another example. The destruction of almost all of the Great Arctic River (Fig. 12) that flowed out through Hudson Bay into the Davis Strait provides a subcontinental example, a model that must have happened many times earlier (Eyles, 1993). Seemingly much more common, however, is interruption rather than total destruction—partial burial of a drainage network by sea-level rise and deposition, followed by sea-level fall and renewed extension with the same orientation and broadly similar location. Carboniferous glaciation in South Africa seems to have followed this model (Visher, 1987). Extreme desertification coupled with development of a rising arch, faulting or a new direction of continental tilt are other factors to consider.

Desertification: As rainfall decreases and vegetation dies in a watershed, what happens to a river? We recognize five possibilities (Fig. 13). First, the river may end in a saline lake (Chari River/Lake Chad in Africa, and the

Svr and Amu Darva Rivers/Aral Sea). Or it may end in a brackish swamp and never reach the sea (Okavango River/Okavango Swamp in Botswana). Thirdly, the river may develop swamps or lakes in midcourse in tectonic lows (Yangtze downstream from Wuhai in Inner Mongolia). Still another possibility is diversion in front of advancing continental or coastal dunes, especially on tradewind deserts and coasts (sand supply exceeds the erosive power of a river with declining discharge); good examples of this are Wadi Malhit in Oman (El-Baz, 2002, p. 26) and Wadi Siebeli southwest of Muqdisho in Somalia. The last and most extreme result is total destruction-either only a few scattered, linear silt pans remain (western Australia) or all the system is destroyed except for converging, short, isolated wadis near divides (western Saudi Arabia, southern Yemen). Some notable studies that illustrate these possibilities include those of Michel (1968, p. 332-334), Van de Graff et al. (1977), Moore (1988), and Thomas and Shaw (1992). Issawi and Mccauley (1993) discussed the reconstruction of the Gilf and Qena systems (precursors to the Nile) over 1,000 km across much of Libya and western Egypt.

Cooper Creek of Australia is a very good example of a long river in an arid region. Some 1,160 km long, this river drains to closed Lake Eyre; its discharge ranges from locally zero to small, although large, intense flash floods sometimes occur (estimating maximum discharge is hard, because flooding is so widespread over a wide, flat watershed). Multiple channels prevail, its course includes shallow ephemeral lakes, and many of its floodplains are salt-encrusted and have stray sand dunes (Tyler et al., 1990). Cooper Creek would seem to be a good model for large, ancient, ephemeral desert streams, but also illustrates how hard it would be to recognize such a stream in ancient deposits.

A spectacular example of a former desert river, over 900 km long, is the former course of the Ergun He in Mongolia and north China, as defined by the 1,000-m contour of a now-dry valley in the Gobi Desert (Fig. 14). This extended, dry valley of the Ergun He, itself a tributary of the Amur, shows just how long the Amur River was before much of the Gobi Desert formed in response to Miocene rejuvenation of the Himalayas. Possibly the headwaters even extended across the Gobi Desert as far west as the closed lake Gaxan Nur and beyond.

ANCESTRY OF MODERN RIVERS

Two major events in Earth history have determined the origin and ages of many of the world's larger rivers: the breakup of Gondwana by continental rifting, principally starting in the Late Jurassic, and worldwide Miocene tectonism (Fig.15).

Dating River Systems: Key questions for every river system, modern or ancient, are: "When did it start" and "When did it end?" Here we concentrate on criteria for existing river systems. In considering these questions, we recognize, along with many others, that most river systems consist of segments of different ages.

Although different answers have been given to these questions (Leopold et al., 1964, p. 421; Mann and Thomas, 1968, p. 187; Potter, 1997, p. 332), we suggest that an existing big river system has three important ages: 1) the time when its present stream network was essentially established or put in place, 2) the age of its oldest segment (when such a segment can be identified, it goes far to establish the age of a river system), and 3) its ancestral age inferred from paleogeography (an example of a paleogeographic age would be a far distant marine delta formed in response to a new marginal collision and continental tilt). Thus, we use Rio Orinoco for its present network, paleo-Orinoco for a former Orinoco with a similar but not identical network, and ancestral Orinico for the river inferred from either deposits relatable to it or from a major paleogeographic event. Determining the above ages involves a broad spectrum of dating techniques-establishing the age of the last marine deposits in a watershed, the time of resurfacing, finding and dating the oldest segment of the river system, dating its oldest alluvial or associated deltaic deposit, determining the age of a major tectonic event that affected its watershed, deductions from the plate tectonic setting of its watershed, apatite fission-track dating or even zirconbased chronologies. Another way to think of this-one that uses most of the above-is to map the inception of drainage across a landscape as has been done in Australia (Wilford, 1991, p.103; Gale, 1992, Fig. 6). The three ages proposed here-integration of present river pattern, age of oldest segment, and its paleogeographic age-help us separate into distinct parts what some have considered to be a continuum of change.



Figure 12. The Great Arctic River destroyed by Pleistocene glaciation (McMillan, 1973, Fig. 23).

The Orinoco River of South America illustrates well the ages of different segments (Diaz de Gamero, 1996). An ancestral or proto-Orinoco flowing north into the Caribbean, with tributaries draining both the Andes and the Guyana Highlands (Fig. 8), is inferred from deltaic Eocene deposits in western Venezuela (paleogeography). This proto-Orinoco abruptly shifted in the Mid-Miocene to the northeast and east with the uplift of the Cordillera Central of Colombia, as confirmed by datable deltaic deposits in central and eastern Venezuela. But after this shift, the river continued to have tributaries such as the Carona and Caura, which flow north and northwest from the Guyana Highlands of Bolivar Province and drain the flat-lying Middle Proterozoic sandstones that underlie the Gran Sabana of southeastern Venezuela. These two rivers may date back to the Early Cretaceous or Late Jurassic. Thus a major tectonic event in its watershed totally reorganized the Orinoco River system, which still retained, however, older southern tributaries such as the Carona and Caura. Thus, judged by the criteria of its oldest tributary, the Orinoco is at least Cretaceous in age, whereas its present drainage pattern was clearly established in the Middle Miocene. Such reorganizations of drainage caused by either tectonics or marine invasions appear to be the rule in many of the world's big river systems.

Establishing the age of resurfacing-the formation of a new surface on which a river flows is easily and directly done by dating lava flows or tuffs that cover a segment of a river, continental glaciation (very efficient and quick at covering even large watersheds), expansion or contraction of sand seas (easy to recognize, but not so easy to date), and the marine deposits of a transgression (easiest to date). Two examples of the role of volcanics in resurfacing are provided by the lava-filled gorges of the Columbia River in Oregon (Tolan et al., 1984) and, on a much smaller scale, by the outpouring of tuffs that filled a valley of the Tiber and diverted a new course through a low col (Alvarez, 1973). Determining the age of the oldest alluvium of a river, or much better, the age of its deltaic deposits, involves standard stratigraphic techniques. In southern Asia, the Indus and Bengal Fans provide evidence of both the initial India-Asia collision (Lindsay et al., 1991; Cliff et al., 2000) and, through studies of their sedimentation rates and petrology, insights into how rates of uplift and provenance change destroyed earlier drainage. Another example is the Miocene uplift of the Andes, which significantly altered much of the drainage of South America, especially that of the Amazon and Orinoco (Hoorn, 1994; Diaz de Gamero, 1996; Potter, 1997).



Figure 13. Idealized end-members of rivers responding to desiccation and desertification. Rivers with declining discharge may end in a saline lake or brackish swamp, have midcourse lakes or swamps (possibly the result of an active tectonic low?), be diverted by migrating dunes as discharge declines, or may be totally destroyed except for isolated, linear salt pans or lakes. Still another possibility is that only small streams in headwaters remain.



Figure 14 Probable abandoned, long tributary of the Kereulin River across the Gobi Desert of Mongolia. Topography from UNESCO (1976).

Unfortunately, most of the rivers included in our research have not been studied with their ages in mind, even if data were available. Hence, establishing the three ages for many of the studied rivers was commonly difficult. Consequently, our discussion of river longevity, although establishing some new insights, clearly shows the need for more research.

Gondwana Breakup: The breakup of Gondwana started as early as the Carboniferous with microcontinents separating from it and impinging the south-central border of Asia (Fig. 4). These rafted blocks created a complex mosaic of fold and thrust belts across Eurasia called Cimmerides (Paleotethys, Carboniferous to Late Cretaceous) and Alpides (Neotethys, Tertiary to present) by Sengör et al. (1988), although principal rifting and separation started in the Late Jurassic and ended in the Early Cretaceous (DeWitt et al., 1988). Initially, at about 150 Ma, the Gondwana supercontinent divided into a western part, Africa-South America, and an India-Antarctica-Malagasy-Australiaeastern part, New Zealand. These events were followed by the almost simultaneous separation of Africa from South America (beginning in the south and ending in the north) and Australia-Antarctica from India-Malagasy between 130 and 120 Ma, and finally the closely synchronous separation of New Zealand from Antarctica and India from Malagasy between 95 and 80 Ma. Early in the process, microcontinents were separating from the northern part of Gondwana and impacting central, but not western, Eurasia. Each of these continent-scale separations within Gondwana started as a major intracontinental rift system filled first by fluvial and lacustrine sediments, followed

	1 0	Time	Riverine & Glacial Lor							gevity Commentary	
Log Time Ma	1.0	Early Pleistocene				ms	ene			ion	
	5	Pliocene	Gondwana breakup	Ocean	c Ocean	ne Tectoni.	Post Mioc	ral Mississippi River	Great Arctic River	Glaciat	Global sea level fall with prograding rivers, world cooling, and continental glaciation
		Miocene		Relict Tethyan	ainage to Arcti	Mioce	5			Contential	5 Mid Miocene, world-wide tectonism closed Tethyan Ocean, opened Red Sea, and uplifted convergent margin of the Americas
ł	20 36	Oligocene	rom	n to	Dr			cest		 3]	25
	54	Eocene	te f	Drai				An			54
	60	Paleocene	Da			। २				Principal collision of India with Asia	
	144	Cretaceous			2			 			144
ĺ		Jurassic		1					Gondwana breakup begins		
	213		Triassic Permian / Exhumed Cambrian channels & terraces in Australia							Early Permian & Late Carboniferious glaciation	
	360 7	Carboniferous									
▼ 1	590 000	Neo- proterozic								River systems inferred only from paleogeography: facies patterns, paleocurrents, provenance and plate tectonic settings	

1. Senegal, Niger, Benue, Orange, Zambezi, Limpopo, Lower Amazon, São Francisco, Uruguay and Paraná; 2. Dneisier, Dnieper, Don, Volga and Ural still flow to the south to remnants of the Teythan Ocean represented by the Black and Caspian Seas; 3.Ob, Yenisey, Lena, Indiqirka, and Kolyma; 4. Present Amazon System, the Orinoco, Magdalena, Seine, Rhine, Rhone, Danube, Vistula, Nile, Amu Darya (draining to the Aral Sea), Indus, Ganges, Yukon, Columbia, Rio Grande (USA) and possibly the Colorado and Fraser; 5. Hwang Ho (Yellow) Yangtze-Kiang, Hong (Red), Mekong, Chao Phraya, Salween, Brahmaputra, and Irrawaddy plus the Tigris-Euphrates and Po; 6. Great Arctic River of Canada.

Figure 15. Longevity of selected river drainages.

by a coastal plain-shelf slope-deep basin drift sequence as an initial narrow, flooded rift with high shoulders widened into a new ocean. See Cainelli and Mohriak (1999) for such a sequence in offshore Brazil. Such rifting formed today's coastal escarpments of eastern Australia, southeastern Brazil, India, and southern Africa, as well as younger escarpments in Norway, Greenland, Labrador, Baffin Island, and those bordering the Red Sea. These rifts and their escarpments range in age from as young as Miocene (the Red Sea) to Cretaceous and possibly older (southern Africa and west coast of India). Such escarpments direct coastal drainage inland down the back slope of the rift shoulder away from the coast, after which it turns parallel to the coast and finally returns to the sea, localized by either a failed arm of a triple junction or a rift oriented perpendicular to the coast.

A surprising number of today's modern rivers have ancestors related to continental separation by rifting and the breakup of Gondwana. Fragments of ancestral Gondwana drainage, mostly late in its breakup, are in southern Africa, India, eastern South America, and Australia. Rivers with this distant heritage include the Senegal, Niger, Benue, Orange, Zambezi, and Limpopo in Africa; the São Francisco, Uruguay, and Paraná in South America; the Godaravi and Krishna in India; and the Murray-Darling and Cooper Creek in Australia. Ancestral drainages are preserved in these regions because they have neither been buried by moraine deposits nor eroded since breakup and all have escaped both subsequent continental collisions and continental glaciations. Where cratons have developed overlying basins and have been repeatedly flooded either by epeiric seas or by distantly derived molasse from a marginal continental collision, old drainage is either destroyed or buried.

Eurasian Megasuture: The northern limit of this intercontinental, 13,000-km-long megasuture (Smith, 1999, Fig. 2) is close to the divide between northern drainage to the Arctic and Atlantic Oceans and drainage to the east and south to the Pacific and Indian Oceans (Fig. 4). This separation demonstrates beautifully that continent-to-continent suturing influences continental tilt just as much as ocean-to-continent convergence does (Fig. 2). There are two notable exceptions. The first is the watershed of the Amur River, the northernmost large river of Eurasia, which drains to the Pacific Ocean. Although the Amur has probably had a complex history since at

least the Late Cretaceous, an Oligocene-Miocene delta at its mouth shows that it was well established by this time (MacDonald and Flecker, 1999). The other significant exception is the southern drainage to the Black and Caspian Seas (Fig. 4).

Relic Tethyan Drainage: The principal collision of Gondwana with Eurasia and the closing of the Tethyan Ocean began with the impact of India against Asia in the Paleocene at about 65 Ma following the earlier impact of microcontinents. This collision incorporated fragments of widely separated oceanic crust in central Asia and finally closed the Tethyan Ocean all across Eurasia, except for remnants represented by Lake Aral (smallest) and the Caspian, Black, and Mediterranean Seas (largest); these last three remnants are underlain in part by oceanic crust. This collision spanned all of the Tertiary (and far longer when microcontinents are recognized), continues to the present day, and consists of an early convergent phase labeled "Cimmerian" and a later phase called "Alpine" by Sengör et al. (1988). The broad lowlands between the Dniester and Emba Rivers with south-flowing drainage to the Black and Caspian Seas in southern Russia, Ukraine, and Belarus (Fig. 4) have as yet escaped this convergence. We interpret this vast lowland region of more than 1,624,000 km² as relic drainage to the former northern passive margin of the Tethyan Ocean. Support for this interpretation comes from Obedientova (1977), who identified a persistent, southern paleoslope of the central Volga River basin starting in the early Carboniferous. Additional support for a long-lived southern paleoslope to the northern edge of the Tethyan Ocean is provided by Kheirov and Khalilov (1990), who identified an Oligocene deltaic facies at the north end of the Caspian Sea. With continued northward movement of the African, Arabian, and Indian Plates against Eurasia, this old southerly paleoslope will eventually be reversed to the north.

Miocene Worldwide Tectonism: Rivers formed by the Miocene event include the Rhine, Rhone, Danube, Seine, and Vistula in Europe. In Africa, the buried canyon under the delta of the Nile River and youthful topography upstream of its valley in the lower 950 km of the Nile below the Aswan Dam are the results of upstream migration of a knick point related to the Miocene Messinian desiccation of the Mediterranean in the Late Miocene (Said, 1981, Figs. 61 and 65), when deformation closed the entrance to the ancestral Mediterranean Sea (Hsu, 1972). This narrow canyon has a basal fill of Late Miocene marine sediments. In Asia, the Brahmaputra, Ganges, and Indus of India and Pakistan, and probably the ancestral headwaters of the Yangtze, Salween, Irrawaddy, Mekong, and Yellow Rivers along the east side of the impingement of India against Asia, formed at that time, even though lower courses are thought to be much younger.

In the Americas, the present Amazon, Orinoco, and Magdalena in South America and the Yukon and Colorado in North America formed during the Miocene. First direct evidence of the Columbia River is channels cut into and capped by basalts. In addition, the Rio Grande River of the United States and Mexico, although believed to have had its beginnings in the Paleocene, was reorganized essentially to its present form by Miocene tectonism (Belcher, 1975). How these Miocene events in the Americas are linked to those in Eurasia is not clear. Klemme and Ulmishek (1991) mentioned, however, that the Miocene was a time of worldwide deepening of basins and uplift, which favored petroleum formation (deeper burial of source rocks and formation of structural traps).

Post-Miocene Rivers: Post-Miocene rivers include the Po and the Danube in Europe; the Jordan in the Middle East in the Pliocene (Garfunkel, 1988, p. 27–29); the lower segments of the Yangtze and Yellow in the Pleistocene/Pliocene after they left the Tibetan Highlands (Barbour, 1936; Hongzhen, 1985, p. 66; Li et al., 2001) and the Zaire in Zaire (connected to the Atlantic in the Pliocene?).

Long-Surviving Rivers: The foregoing discussion of longevity clearly shows that big rivers survive longest on passive margins with persistent continental tilt and ample, long-term rainfall - without "accidents" of continental glaciation, desertification, and widespread volcanism. Both modern and ancient rivers support this conclusion. In the Americas, the ancestral lower Mississippi River can be identified by deltaic deposits (Cotton Valley and Smackover Formations) in the Upper Jurassic and is traceable back to deltaic deposits of the upper and Lower Carboniferous in the Illinois Basin, almost 250 Ma (Swann, 1963; Archer and Greb, 1995). Another possibility is the establishment of more links between present rivers and those of Gondwana (Veevers and Tewari, 1995, Fig. 42) and possibly even late Pangea. Although little information seems to be available, the Russian rivers Ob, Yenisey, Kolyma, and Lena all drain to the same passive margin of the Arctic Ocean and could be older than present evidence suggests. Conversely, it is very clear that orogenies both rapidly destroy and create rivers.

The Wilson Cycle of plate separation \rightarrow new ocean \rightarrow ocean closure \rightarrow convergent margin (oceancontinent, continent-continent or microplate-continent) is the fundamental control on big-river longevity (via persistence of passive margins and continental tilt) and also underlies the kinds and durations of continent-wide landscapes (Ollier, 1997). Thus, the existence of big rivers, their longevity, and continental landscapes all relate to the history of migrating plates.

CONCLUSIONS

Plate tectonics, climate, changes in relative base level, and volcanism are the principal processes that have controlled the size of the drainage basins of big river systems, their stream patterns, and longevity since at least the Archean, some 4.2 to 4.3 billion years ago. Together, these four processes predominantly govern the geologic evolution of today's large rivers of the watersheds of large rivers (Table 5). Of the four, plate tectonics is, in the long course of Earth history, easily the most dominant, although both climate and base-level changes, when extreme, can be decisive. Volcanism probably was of most importance in the early Earth

Plate Tectonics: The first-order control on big river systems is plate tectonics, for four reasons:

- 1. It creates the principal relief of the continents, such as plate-margin mountain belts and sutures, and thus continental tilt, subcontinental rifting, regional domes and uplifts, and controls the position, size, and life spans of the sedimentary basins of continents on a wide range of scales.
- 2. Ocean-continent convergence and continent-tocontinent sutures are the first-order continental controls on big river systems because they determine continental tilt, whereas second-order controls are doming (hotspots), large-scale intracontinental rifts, and deep crustal fractures.
- Big river systems are, in broad terms, relatable to the Wilson Cycle of hot spot → dome with radial drainage → initial stage of continental rifting → arm of the sea → small ocean → large ocean and passive margins with large rivers → small, closing ocean with

an active margin (ocean-continent or micro-continent or continent-continent convergence) \rightarrow new direction of continental tilt and drainage asymmetry. Early in the history of these two new passive margins, high coastal escarpments are likely to divert new drainage inland away from a direct route to the sea.

4. The fundamental control on the length of a large river, its drainage area, and the orientation of its watershed is regional tectonics—perhaps best thought of as *tectonic accommodation* in analogy with the concept of *accommodation space* of sequence stratigraphy (the space available for deposition that determines sedimentary facies). It is tectonic accommodation that determines the response of a river (orientation, size, and shape of its watershed) to differential subsidence, uplift, and sedimentation within its watershed. Stated differently, tectonic accommodation determines the lows that a river follows across a regional slope.

Present Continents: The principal determinant of the world's present big river systems is the closing of most of the Tethyan Ocean across southern Eurasia, culminating in the Miocene and the Miocene uplift of the Andes.

In Eurasia this suture created vast highlands from Spain to Vietnam, destroyed or backtilted the majority of rivers draining to the north side of the Tethyan Ocean, and created many new rivers in China, Tibet, Vietnam, India, Pakistan, and Europe, such that only the watersheds of the Emba, Ural, Volga, Don, Dnepr, and Dnestr have survived. The northern limit of Gondwana closely coincides with the northern limit of these sutured highlands.

The ocean-to-continent convergence of the western Americas affects a smaller amount of the world's present large river systems, but provides an ideal model for initial drainage in the Wilson Cycle. Africa and Australia share much in common with respect to continental drainage, because both have mostly passive margins and large semi-arid areas. Both seem to represent two related stages: Australia is a still-intact continent unaffected by Cenozoic rifting whereas rifting began in Africa in the Miocene. Could it be that together all six present nonglaciated continents represent all the possibilities of continental drainage?

Other Interruptions of Big Rivers: Climate (glaciation and desertification), changes in base level, and volcanism all can interrupt and even destroy a big

river system. Of the three, most well established is glaciation in the northern hemisphere and desertification in Africa and Australia during the Quaternary and Late Tertiary. Volcanism, although decisive on local and even basinwide scales, may have been continental in scale only in very early Earth history. Marine invasions (change in base level) represent still another means of major drainage modification and perhaps even total interruptions as well.

Longevity: Many of the world's present rivers, both in Eurasia and the Americas, date from the Miocene. Some rivers are much older, however, and originated earlier in the Mesozoic and a few as far back as the Carboniferous. The oldest rivers occur on passive margins that somehow escaped destruction, total resurfacing, or reverse tilting by colliding plates. At the other extreme, a few such as the Yellow and Yangtze are thought to have only a Pliocene-Pleistocene age in much of their lower courses, and the present Nile only formed in the Pleistocene.

Compelling Tectonic Control of Large Rivers: Tectonic control of large river systems is compelling. Big rivers follow topographic lows, virtually all of which are formed by tectonics from local to continental scales—continental tilt related to sutures or convergent margins, aulacogens/rifts, axes of subsiding basins, and fracture zones and faults. Hence, rivers can be studied to infer subsidence and structure, or, conversely knowing or assuming a given structural configuration, a river's course should be predictable both today and in the past.

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Table 5: Evolution of Modern Drainage

Glaciation in Carboniferous in southern hemisphere

Resurfaces much of former landscape disrupting earlier drainage

Rifting of Gondwana and its consequences

- 1. Dismembers and disperses earlier drainage of Gondwana
- 2. Rifted escarpments of newly rifted continents direct much drainage inland (long way to the sea) and failed rifts (aulacogens) focus big rivers to passive margins
- 3. Some of these continents drift into arid zones and have few large rivers, and some drift into wet climates and have large rivers

Cretaceous events

1. Eustatic

- A. Maximum marine flooding in Cretaceous obliterates much previous drainage
- B. Progressive withdrawal of Cretaceous seas from highstand exposes much new land surface for trunk streams
- 2. Continued global rifting of Gondwana through Late Cretaceous

Worldwide Miocene Tectonism

Convergence in Eurasia (Atlas-Alpine-Zagros-Himalayan Orogeny) and along west side of the Americas is biggest single factor in modern drainage

- 1. Produced highlands and continental tilt away from active margins and mega sutures
- 2. Parallel drainage in fold belts
- 3. "Linear" rivers following regional strike-slip faults and transforms
- 4. Inception of world-wide cooling and widespread desertification

Notable Pleistocene Rivers

Large rivers that lack significant Late Tertiary deltas and those created by Pleistocene ice sheets

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As we began to write, we realized that two papers were needed—one to present our conclusions (Part I) and the other to make available to everyone the scattered literature on the origin of many of the world's large rivers (Part II).

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APPENDIX 1 Modern Big River Systems

River Name, Length (km), and Age	Structural Setting and Key References
Africa	
1. Benue, 1,068 Proto Benue since Late Cretaceous separation of South America from Africa via triple junction	Much of lower course follows Benue Rift (aulacogen) perpendicular to passive margin (Frostick and Reid, 1989, Fig. 3; de Reijers et al., 1997). Mostly Cretaceous bedrock, but Precambrian in headwaters
2. Limpopo, 1,600 Probably since separation of Africa from Australia, but present drainage network since Pliocene-Pleistocene (Moore, 1988)	Flows mostly on Precambrian bedrock, but lower course on side of Mozambique Basin up to 8 km thick (Exxon, 1985, panel 16); seemingly too thick for present river?
3. Niger, 4,160 Proto Niger since Late Cretaceous (Albian-Santorian) or earlier, but present river from Pleistocene pluvial overflow of low divide in Malí?	Rises in Fouta Djalon Highlands in Sierra Leon close to Atlantic, but flows inland before turning southeast toward delta; lower course follows Bida Rift (aulacogen) to passive margin (NEDECO, 1959; Hospers, 1971; Frostick and Reid, 1989, Fig. 3; de Reijers et al., 1997). Precambrian in upper and middle course, but thin Cretaceous in lower
 4. Nile, 6,670 Three major segments: the oldest dates from 40 Ma, although the present Nile dates from the Pleistocene; mouth has spectacular Miocene canyon related to giant Mediterranean salt pan (Messinian Event) 	Unusual river flows parallel to Red Sea Rift over craton with complex structural history to passive margin of remnant Tethyan Ocean (Said, 1981, 1994; Issawi and McCauley, 1993). Lower course in shallow embayment, but delta up to 10 km thick (Exxon, 1985, panel 11). Great range of rock types includes Tertiary basalts in Ethiopia
 5. Orange, 1,860 Offshore deposits existed in Late Cretaceous, but mouth shifted several times between 28° and 31°S; present river mouth since Miocene- Pliocene (Dingle and Hendey, 1984) 	Crosses most of southern Africa, and exceptionally, both headwaters and mouth begin and end at rifted passive margins. Precambrian in lower and middle parts, but upper part in Paleozoic rocks. Headwaters only 270 km from Indian Ocean
 Senegal, 1,609 Inward-flowing headwaters date from initial separation of South America from Africa in Early to Late Cretaceous. See Niger River 	Headwaters only 240 km from Atlantic, but flows inland away from rifted passive margin and Fouta Djalon Highlands and turns north parallel to coast before entering Atlantic Ocean. Mostly Precambrian bedrock except for lower coastal basin

7. Zaire (Congo), 4,370 Developed in Pliocene following coastal capture of large lake?	Intracratonic basin draining to passive margin (Cahen, 1954, ch. 16 plus Figs. 88–91; Karner and Driscol, 1999); part of lower course overlies Bakongo Aulacogen (Deffontaines and Chorowicz, 1991, p. 257, Fig. 7). Most of basin covered by Neogene and Pleistocene, but near coast is a narrow belt of Precambrian
 Zambezi, 2,660 Headwaters since uplift of Karro Basin in Cretaceous, but much of present course only since Pliocene-Pleistocene? 	Complex and includes intracratonic Karro Basin in headwaters, intracontinental rift in middle course, and 5 km delta over-rift on passive margin (Exxon, 1985, panel 16; Nugent, 1990; Thomas and Shaw, 1992). Tertiary in upper half and mostly Precambrian in lower
Australia	
 Cooper Creek, 1090? Paleocene(?) from separation of Australia from New Zealand, as is the Murray-Darling 	Drainage down back slope of rifted continental margin (Great Dividing Range) to closed basin of Lake Eyre (Tyler et al., 1990)
10. Murray-Darling, 1,704First related deposits in Paleocene (Brown, 1989)	Starts only150 km from Pacific Ocean in Great Dividing Range on ancient passive margin and crosses thin Tertiary, pericratonic Murray Basin to passive margin of Southern Ocean. Headwaters in Precambrian rocks
Eurasia	
 11. Amur, 4,416 Present pattern since Pliocene(?), but in existence at least since the Miocene (Varnavskiy et al., 1992). Some segments since Early Tertiary? 	One of the world's most complex large river patterns (perhaps connected to the Yellow before Gobi Desert developed and may have captured some headwaters of the Lena?). Southern arm has headwaters only 150 km from Sea of Japan. Great variety of sedimentary and igneous rocks in watershed, including Quaternary basins
12. Bramhaputra (Tsangpo), 2,840 First subsurface evidence of India-Asia collision about 40 Ma and modern delta about 10 Ma	Upper longitudinal course follows major suture, but lower occupies a foreland basin draining to passive margin and back arc basin, Bengal Fan on oceanic crust (Lindsay et al., 1991). Bengal Fan is 16 km thick (Exxon, 1985, panel 11)
13. Chao Phraya, 1,200 Miocene or later?	Follows distal structural grain of impact of India against Asia in central Thailand
14. Danube, 2,860 Proto-Danube identified in Middle Miocene in Austrian Alps, but present course to Black Sea through Iron Gate in Pleistocene?	Alpine foreland basin in headwaters and Pannonian Basin (complex back-arc basin on continental crust produced by Africa impacting Europe) for most of middle and lower course (Neppel al., 1999). Widespread Neogene and Quaternary deposits in lowlands, but mostly Mesozoic and Tertiary sediments in headwaters

15. Don, 1,870 Dates from passive margin of Tethyan Ocean	Chiefly Tertiary and Cretaceous bedrock.
 16. Dnepr, 2,200 Southward course to Black Sea inherited from passive margin of former Teythan Ocean. Stratigraphic evidence since the Miocene (Matoshko et al., 2002) 	Mostly Tertiary and Cretaceous bedrock
17. Dnestr, 1,550Relic Tethyan drainage with Miocene overprint?	Westernmost of relic Tethyan drainage,but headwaters in Miocene underfilled foreland basin of Carpathian Mountains
18. Emba, 490 Miocene?	Headwaters in southernmost foothills of Urals. Smallest of relic Tethyan drainages
 19. Ganges, 2,510 Miocene (Brookfield, 1993, p. 61), although first evidence of India-Asia collision about 40 Ma 	Underfilled foreland basin between Himalayas and Indian craton, but delta in back-arc basin of Bengal Fan on oceanic crust (Lindsay et al., 1991, Fig. 21). All but headwaters on Quaternary alluvium
20. Godavari, 1,500 Ancestral Gondwana breakup river (Radhakrishna, 2001) probably Late Jurassic–Early Cretaceous	Backslope (long way to the sea) on Deccan Traps extruded when India separated from Gondwana. See also the Krishna River
21. I1i, 840 Miocene or later?	Flows northwest on molasse cover of former Tethyan Ocean
22. Indigirka, 1,726 Middle and upper course Late Cretaceous to Paleocene? See also the Kolyma below	Drains to passive margin of Arctic Ocean (Siberian Sea) from convergent margin fold belt(Momskly and Cherskly Ranges), while lowermost course follows a narrow graben to the sea; offshore is a large submarine canyon (Grantz et al., 1986)
23. Indus, 3,180 Middle Miocene (Brookfield, 1993, p. 61; Cliff et al., 2000)	Foreland basin up to 6 km thick localized along Indus suture with Indus Fan at mouth (Schroder, 1993). Most of middle and lower course runs on Quaternary fill. Offshore fan is 10 km thick (Exxon, 1985, panel 11).
24. Irrawaddy (Ayeyarwady), 2,300 Oligocene?	Suture zone in back-arc basin partly on oceanic crust (Brookfield, 1998, p. 295). Lower course follows elongate Neogene basin. Offshore fan 11 km thick (Exxon, 1985, panel 11)
25. Jordan, 322 Principally in the Pliocene, but possibly earliest headwaters in Middle to Late Miocene? (Garfunkel, 1988)	Localized along left-lateral Dead Sea transform fault in response to northward drift of the Arabian plate and opening of the Red Sea in the Miocene (Garfunkel, 1988; Horowitz, 2001). Wide range of rocks in small watershed includes basalts

26. Kolyma, 1,290 Paleo-Kolyma dates from Late Cretaceous to Paleocene?	Empties to passive margin of Arctic Ocean (Siberian Sea) and sourced in convergent margin (Momsky fold belt); mouth at end a major submarine suture and Kolyma sea valley (Grantz et al., 1986)
27. Krishna, 1,290 Ancestral Gondwana breakup river (Radhakrishna, 2001) starting in Late Jurassic-Middle Cretaceous?	Like its twin the Godavari, the Krishna flows down the backslope (long way to the sea) on tilted Deccan Traps extruded when India separated from Gondwana
28. Lena, 4400 Lower Cretaceous and possibly much older?	Flows to Arctic passive margin with lower course in foreland basin (Sokolov et al., 1989) between Siberian Craton and Verkhoyansk collisional range (Zhukovskiy, 1967; Rodionov, 1974; Zonenshain et al., 1990, p. 25–26; Huh et al., 1998, p. 1660). Mouth overlies termination of Mid Atlantic Rift. Headwaters of eastern tributary, the Aldan, only 40 km from Sea of Okhotsk
29. Mekong, 4,500 Headwaters since Miocene, but present course since Pleistocene (Brookfield, 1998, p. 310)?	Middle and upper course follows right-lateral sheer of Indian indentation into Asia, whereas lower course crosses complex structure before reaching back-arc basin of South China Sea (Hutchison, 1989, p. 67–69; Brookfield, 1998, p. 243–294, Fig. 23). Mostly Mesozoic sedimentary rocks, but much Quaternary near mouth
30. Ob, 5570 Ancestral Ob in Upper Jurassic and Lower Cretaceous and paleo-Ob in Oligocene (Peterson and Clarke, 1991).	Flows to Arctic passive margin. Mesozoic–Tertiary basin underlain by dense north–south system of faults. World's largest estuary
31. Po, 691 Pliocene?	Foredeep (perisutural basin) between passive Alps and actively thrusting Apennines (Ori, 1993, Fig. 2). Most of basin floored by Quaternary alluvium
32. Red (Hong), 1,125	Follows right-lateral suture between impacting Indian and Asian plates for most of upper and middle course (Brookfield, 1998, Fig. 8); beheaded by Yangtze in Late Pleistocene (Barbour, 1936)
33. Rhine, 1,360 Middle Miocene	Rift formed by collision of Adria Microplate with Europe via Alpine Orogeny (Quitzow, 1974; Andres, 1989; Sissingh, 1998, Fig. 19); mouth localized by graben system (Zagwijn, 1974, Figs. 1–2); rift system continues northward under the North Sea. Complex Mesozoic bedrock in headwaters, Paleozoics in middle course, and Quaternary at mouth
34. Rhone, 810 Upper Miocene	Occupies rift formed by Alpine Orogeny — during collision of Adria Microplate with Europe (Sissingh, 1998, p. 293–294)

35. Salween, 3,060 Headwaters since Oligocene?	Mostly follows right-lateral eastern shear margin of India-Asia impact (Brookfield, 1998, p. 293–294, Fig. 23). Chiefly Neogene deposits in middle and lower course
36. Seine, 760 (and paleovalleys of English Channel)Possibly coincident with Alpine Orogeny in Miocene?	London-Paris intracratonic basin (Auffret et al., 1980; Smith, 1985; Gibbard, 1995; Lautridou et al., 1999). Mesozoic and Tertiary sediments underlie watershed
37A & 37B. Syr Darya and Amu Darya, 1,790 & 1,450 Miocene or younger?	Backtilted twin sisters on molasse apron
38A & 38B.Tigris-Euphrates, 1,960 & 2,740 Latest Tertiary(?), although time of flooding through Straits of Hormuz uncertain. Pliocene?	Twin sisters in narrow foreland basin in front of Zagros Mountains (Goff et al., 1994). Grabens in middle course of Euphrates (De Ruiter et al., 1994)
39. Ural, 2,430 Relic Teythan drainage away from the uplift of the Urals in the Carboniferous?	Relict drainage to passive margin of former Tethyan Ocean
40. Volga, 3,350 A least since Miocene (Obedientova, 1977; Crasquin, 2000), but likely since early Cretaceous?	Relict from passive margin to Tethyan Ocean (Kheirov and Khalilov, 1990)
41. Yangtze (Changjiang), 6,380 Middle and Late Pleistocene (Hongzhen, 1985, p. 27) in most of lower and middle course and Quaternary capture of headwaters of Red (Barbour, 1936; Brookfield, 1998, p. 310).	Has complexly faulted and sheared headwaters because of India-Asia collision in fold belt (Brookfield, 1998, p. 310) and drains to back-arc basin of East China Sea. No significant delta at mouth
42.Yellow (Hwang He), 4,670 Middle and Late Pleistocene for lower reaches, but headwaters captured in latest Tertiary Quaternary (Hongzhen, 1985, p. 27; Brookfield, 1998, p. 310)?	Complex response to impact of India against Asia and desertification in upper course. No significant delta at mouth
43. Yenisey, 5,550 Cretaceous–Early Tertiary similar to Ob?	Flows subparallel to fault system to passive margin of Arctic Ocean across West Siberian Plain, but many tribuaries flow south from volcanic plateau before joining trunk stream. Mostly Quaternary deposits in middle and lower course

The Americas	
 44. Amazon (includes Amazonas, Solimões, & Marañón), 6,240 Backtilted to Atlantic in Middle Miocene by Andean Orogeny (Hoorn, 1994), but proto-Amazon at least since Cretaceous and possibly Triassic (Grabert, 1978) 	Exits Andes at Marañon Basin and mostly follows sag of Solimoes and Amazonas Basins between Guiana and Brazilian Shields (in part over Neoprotozoic aulacogen) with estuary above Cretaceous rift (Hoorn, 1994; Milani and Zalán, 1998). Vast alluvial fill of Quaternary–Neogene age overlies three large basins after main trunk leaves the Andes
45. Colorado (USA), 2,333 Most development since Middle Miocene, about 14 Ma	Lower part controlled by Basin and Range block faulting; upper part developed by headward erosion and drainage of Tertiary lakes. Drains to rift basin of Gulf of California. Chiefly Mesozoic and Paleozoic rocks underlie watershed
46. Columbia, 1,950First firm evidence in western Washington in Miocene, but some headwaters possibly older than Miocene uplift of Coast Range?	Drains to convergent margin of Juan de Fuca Plate subducted by North American Plate (Tolan et al., 1984; Snavely, 1987). Many rock types in accretionary terrane of watershed, but Tertiary Columbia River basalts notable and influenced course
47. Fraser, 1,100 Late Cretaceous?	Largely controlled by internal sutures of accretionary margin, but course altered by lavas, tectonics, and glaciations (Lay, 1940). Complex rock types of accretionary terrane include basalts
48. Magdalena, 1,530 Middle Miocene	Follows thrust sheet valleys of Andean fold-fault system developed in foreland basin as Nasca Plate impinges South America (Duque-Caro, 1979; Dengo and Covey, 1993; Díaz de Gomero, 1996; Potter, 1997), but crosses major thrust in lower course
49. Mackenzie, 4,240 Pleistocene integration of three different preglacial rivers, one to Hudson Bay and two to Arctic Ocean; offshore delta in Pliocene. An ancestral Mackenzie of Paleocene age underlies the present delta (Hawkings and Hatfield, 1975)	Lower course in foreland basin bounded by Peal Plateau and western Canadian Shield (Stott et al., 1993, p. 450–457; Duk-Rodkin, 1994). Delta bounded by shear faults
50. Mississippi, 3,791 Lower valley of Mississippi Embayment since Late Jurassic, but has ancestors back to Mississippian deposits of Illinois Basin (Swann, 1963)	Mississippi Embayment overlies Proterozoic aulacogen, which also underlies parts of intracratonic Illinois Basin (Mann and Thomas, 1968; Potter, 1978; Kolata and Nelson, 1990). Sedimentary rocks dominated by Paleozoics underlie most of the watershed (but alluvial fill of lower valley notable). Headwaters of Ohio and Mississippi established in Mesozoic

51. Missouri, 3,726 Pleistocene	Much of middle and lower course is near glacial margins of multiple glaciations on classic craton. Mixed Mesozoic and Paleozoic bedrock
52. Orinoco, 2,740 Middle Miocene, but proto-Orinoco tributaries of Guyana Shield much older	Foreland basin (in front of developing Andes) bounded by Guyana Shield; oblique strike-slip island arc diverted mouth from Caribbean to Atlantic? (Grabert, 1978; Díaz de Gamero, 1996; Potter, 1997). Vast Neogene-Quaternary plain bounded to south by Guyana Shield and by Mesozoic and Paleozoic rocks of Andes to north and west
 53. Paraná, 4,500 Most Brazilian segments since Late Cretaceous(?), but mouth diverted to present Rio de la Plata Estuary about 2.4 Ma 	Classic intracratonic Paraná Basin for much of course (follows basin axis in part), but present estuary localized by Cretaceous rift (Stokes et al., 1991, Figs. 5, 12; Parker et al., 1994; Potter, 1997). Upper Paleozoics and Mesozoic sediments and volcanics bounded by Precambrian crystalline rocks
54. Paraguay, 2,950 Mid-Tertiary	Foreland basin in front at Andes overlaps Brazilian Shield and Paraná Basin (Marshall et al., 1993; Potter, 1997, p. 339). Mostly Neogene and Quaternary sediments bounded by Paleozoic- Mesozoic rocks and Precambrian basement
55. Rio Grande (USA), 2,870 Early Tertiary (first recognized in Paleocene) with renewed development in Oligocene- Miocene (Galloway et al., 2000, Figs.5-12)	Rio Grande rift in upper half, superimposed on Laramide uplifts in middle course and Rio Grande Embayment in lower course (Belcher, 1975, Figs. 34, 54, 59; Winker, 1982, Fig. 9; McKenna, 1997)
56. São Francisco, 2,800 Late Cretaceous except for Eocene(?) capture of lowermost, southeast-trending segment to Atlantic	Upper course follows axis of Cretaceous-Tertiary São Francisco Basin, which overlies Proterozoic Bambui Basin (Potter, 1997; Karner and Driscoll, 1999, p. 33); lower course crosses Jatoba Rift to Atlantic
57. Uruguay, 1,250 Late Cretaceous?	Margin of uplifted intracratonic Paraná Basin, but mouth localized by Cretaceous rift (Stokes et al., 1991, Figs. 5, 12). Principally Upper Paleozoic sedimentary rocks, volcanics, and minor Precambrian crystallines
58. Yukon, 3,000 Central and lower parts since uplift of Alaska Range in Miocene, with headwaters diverted westward by early glaciation, 2.6–2.9 Ma	Much of middle and lower course follows right- lateral shears to Bering Sea (Exxon, 1985, panel 1), but upper part first flowed southward to the Pacific (Tempelman-Kluit, 1980, Fig. 5; Ager et al., 1994; Duk-Rodkin et al., 2001)

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Big Rivers Worldwide Part II Annotated Bibliography

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INTRODUCTION

Great river systems transfer most of the water, mud, silt and sand, nutrients, and inorganic chemical elements from the continents to the world ocean. Thus, they are key to understanding many modern global systems and their cycles. Consequently, they have long received much study from engineers, hydrologists, geomorphologists, and geographers plus, more recently, those interested in the global transfers from continent to ocean to atmosphere. The geology of these modern river systems deserves equal attention - how have they been affected in the past by changing climates (desertification and glaciation), by the migration and collision of continental and oceanic plates, or more locally, by faulting, tilting, and differential subsidence in their watersheds? Answers to such questions for modern rivers also have great relevance for understanding and exploring the resources of ancient basins and for geomorphology, physical geography, and tectonics. To help resolve these problems, we prepared this annotated bibliography, which is based on a widely scattered world literature in English, German, Spanish, French, Portuguese, Russian, and Chinese in many international journals as well as in many hard-to-find regional journals, proceedings, and university journals. The objective of this bibliography is to marshal the key literature about the origin and geology of great rivers and their watersheds worldwide and thus provide the basis for future analytical studies in many different fields. Here we focus on rivers not displaced by Pleistocene continental ice sheets.

This annotated bibliography of over 300 references consists of general background references, followed by specific studies organized by continents. Modern as well as ancient rivers are included. Each annotation tries to capture the principal idea of the reference and may also include some key details. The search engine GEOREF (American Geological Institute) was used repeatedly, and yielded some unusual "finds," but we confirm that there is no substitute for plodding, day-in/day-out bibliographic search in a good library combined with a careful examination of references in articles. In many articles information about big rivers is incidental to the main theme. Thus, keywords alone are often insufficient to identify important articles. Because this bibliography is worldwide in scope, we made special effort to find non-English language articles.

Simple as it seems, organizing this literature was an important step forward. General or process papers form one part of the bibliography, and included are papers on plate tectonics, basin formation, river mechanics, and fluvial geomorphology. These are followed by studies related to specific rivers on the different continents — Africa, Australia, Eurasia, and the Americas.

BACKGROUND REFERENCES

Audley-Charles, M.G., Curray, J.R., and Evans, G., 1977, Location of major deltas: Geology, v. 5, p. 341-344.

Pioneering, perceptive article recognizes four major drainage patterns (p. 341–342): cratonic and passive margins that may be interrupted by an old orogenic belt such as the Appalachians; African-type (drainage to all rifted margins), parallel to and within grain of orogenic belts (Magdalena, Yukon, Brahmaputra, and Irrawaddy), as well parallel to but in front of the orogenic belt (Ganges, Tigris-Euphrates, Lena, Indus, Orinoco, Rhone, and Mackenzie); and those with transverse drainage (Snake-Columbia and Fraser). See also Audley-Charles et al. (1979).

Audley-Charles, M.G., Curray, J.R., and Evans, G., 1979, Significance and origin of big rivers: A discussion: Journal of Geology, v. 87, p. 122–123.

Useful and important comments on Potter (1978), principally on the dependence of large river systems on plate tectonics (and consequent locations of great deltas and subsea fans). *Well worth reading today*.

Baker, V.R., 1997, Mega floods and glaciation, in Martini, I.P., ed., Global changes in postglacial times: Quaternary and Permo-Carboniferous times: Oxford, Oxford University Press, p. 98–108.

Northern hemisphere Quaternary glacial floods, called *jökulhlaups*, plus discussion of probable ones in Gondwana — a little-appreciated way of river reorganization in the past? See Benn and Evans (1998, p. 122–123 and 341–343).

Baker, V.R., and Kornastu, G., 1999, Extraterrestial fluvial forms, in Miller, A.J., and Gupta, A., eds. Varieties of fluvial form: Chichester, Wiley, p. 11–30.

Good review of fluvial forms on the Moon and Venus (lava?) and on Mars and Earth (water).

Benn, D.J., and Evans, D.J.A., 1998, Glaciers and glaciation: London, Arnold, 734 p.

Pages 122–123 and 341–343 summarize glacial outbursts, *instantaneous big rivers* that seem to last less than a day but have been estimated to have had discharges as large as 2 to 20 times the mean flow of all the world rivers to the oceans (p. 343).

Bishop, P., 1995, Drainage rearrangement by river capture, beheading and diversion: Progress in Physical Geography, v. 19, p. 449–473.

Argues that stream diversion is more probable than stream capture; useful maps and line drawings.

Bridge, J.S., 2003, Rivers and floodplains: Oxford, Blackwell Science, 491 p.

Excellent background text provides processes (Chs. 5-8) and products (9-10) plus two helpful appendices. Keep this book handy when you study the geology of big river systems, modern or ancient.

Burbank, D.W., McLean, J.K., Bullen, M., Abdrakhmatov, K.Y., and Miller, M.M., 1999, Partioning of intermontane basins by thrust-related folding, Tien Shan, Kyrgyzstan: Basin Research, v. 11, p. 75–92.

Figure 6 shows how both riverine antecedence and wind gaps form, depending on the relative importance of discharge, rock resistance, and rate of uplift.

Burbank, D.W., and Pinter, N., 1999, Landscape evolution: The interactions of tectonics and landscape: Basin Research, v. 11, p. 1–

Argues that orographic precipitation, erosion, and tectonic style are all interrelated. In other words, there may be a strong feedback between internal tectonics and external earth processes.

Busby, C.J., and Ingersoll, R.V., eds., 1995, Tectonics of sedimentary basins: Oxford, Blackwell Science, 577 p.

Thirteen chapters rich in background material for the study of big rivers. See, for example, Hack's Law (Fig. 3.27) and axial sedimentation in rifts. Over 1,100 references.

Carey, S.W., 1967, Scale of geotectonic phenomena: Journal of the Geological Society of India, v. 3, p. 97–105.

Figure 2 uses a log-log scale to schematically plot event duration versus scale of a wide range of tectonic and sedimentologic events — a key diagram to place big river systems in a wider context.

Choubert, G., and Faure-Muret, A., 1976, Atlas géologique du Monde: Paris, UNESCO, various scales.

Essential for big river studies along with the Exxon (1985) tectonic map of the world.

Cox, K.G., 1989, The role of mantle plumes in the development of continental drainage patterns: Nature, v. 342, p. 873-877.

> Examples from Brazil, Africa, and India illustrate the importance of plumes on drainage patterns. Important pioneering idea paper relevant to regional drainage and erosion surfaces.

Crasquin, S., Coordinator, 2000, Explanatory notes, Atlas Peri-Tethys, Paleogeographical Maps: Commission Geological Map of the World, UNESCO, Paris, 268 p.

This volume accompanies 24 maps of the peritethys region (Europe, western Asia, and northwestern Africa). These maps range from Moscovian (312-305 Ma) to Pleistocene and show areas of volcanics, ocean basins, epicontinental marine deposits, and continental deposits all on orthographic projections. Essential reading.

Czaya, E., 1981, Rivers of the world: New York, Van Nostrand Reinhold Co., 246 p.

Good introduction to fluvial geography. Excellent data on most large rivers includes general description, distinctive characteristics, etc. Outstanding resource.

Degens, E.T., Kempe, S., and Sathy, N.A., 1988, Transport of carbon and minerals in major world rivers, lakes, and estuaries. Part 5; Proceedings of a workshop arranged by the Scientific Committee on Problems of the Environment (SCOPE) and the United Nations Environmental Programme (UNEP) at Fairbanks, Alaska, U.S.A., August 11-16, 1986: Selbstverlag des Geologisch-Palãontologeschen Institutes der Universität Hamburg, 422 p.

> Although emphasis is on the transport of the chemicalorganic load of rivers, most of the papers present excellent summaries of the history and hydrology of the rivers they discuss.

Dewey, J.F., and Burke, K., 1974, Hot spots and continental break up: Implications for collisional orogeny: Geology, v. 2, p. 57–60.

> Pioneering paper on big-picture tectonics, and major rivers and their deltas, shows that many rivers flow down aulacogens localized by one arm of a long-abandoned rr-r triple junction.

DeWitt, J.J.L., 1988, Geological map of sectors of Gondwana reconstructed to their disposition about 150 Ma: American Association Petroleum Geologists/University Witwatersrand, Johannesburg, scale 1:10,000,000.

Basic to understanding how drainage evolved from Gondwana.

Dickinson, W.R., 1988, Provenance and sediment dispersal in relation to paleotectonics and paleogeography of sedimentary basins, in Kleinsphen, K.L., and Paola, C., eds., New perspectives in basin analysis: New York, Springer Verlag, p. 3–25.

> Figures 1.6, 1.11, and 1.12 show world orogenic belts and some drainage. Table 1.4 summarizes big river courses and dispersal systems. Big thinking well done.

Douglas, I., 1969, The efficiency of humid tropical denudation: Transactions of the Institute of British Geographers, v. 46, p. 1–16. Concludes that erosion in tropical climates reaches a state of equilibrium. Rates of erosion increase when equilibrium is disturbed by tectonism or climatic changes. Important concept for rates of erosion and ways in which drainage systems change.

Embleton, C., 1972, Vicissitudes of the course-changing river: Geographical Magazine, v. 44, p. 601–606.

> Emphasizes the importance of headward erosion and stream capture in the general evolution of river systems. Examples of antecedent and superposition presented and evaluated. Semipopular paper.

Exxon, 1985, Tectonic map of the world: Tulsa, American Association of Petroleum Geologists Foundation, varying scales.

Nineteen maps in 17 sheets show basins and structural features; includes isopachs of larger subsea fans. Vital for study of big river systems. See also Choubert and Faure-Murat (1976).

Flemings, P.B., and Jordan, TE., 1989, Stratigraphic modeling of foreland basins: Interpreting thrust deformation and lithospheric rheology: Geology, v. 18, p. 430–435.

> Foreland basins are overfilled when supply exceeds subsidence (principal river flows perpendicular to the tectonic front) and underfilled when it flows parallel to the tectonic front.

Ford, David, and Golonka, Jan., 2003, Phanerzoic paleography, paleoenvironment and lithofacies maps of the circum-Atlantic margins: Marine and Petroleum Geology, v. 20, p. 249-285.

> Sixteen figures display continental configuration, lithofacies, climate, etc., using the sequences of Sloss. Figure 16, a table, ably summaries 14 of these maps and Figure 1 combines a world sea level curve with magnetic events and stratigraphic terminology. Important backbround paper. See also Golonka et al. (2003)

Frather, A., ed., 1984, Great rivers of the world: Boston, Little, Brown and Co., 159 p.

> A nontechnical description of river voyages by a variety of writers. Good simple maps and pictures, but minimal geologic information. Background reading.

Friend, P.F., 1978, Distinctive features of some ancient river systems, in Miall, A., ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 531–542.

> Thoughtful article suggests that many ancient river systems may have ended in terminal fans rather than the incised valleys of many present-day streams (the result of Quaternary events).

Frostick, L.E., and Reid, I., 1989, Is structure the main control of river drainage and sedimentation in rifts?: Journal of African Earth Sciences, v. 8, p. 165–182.

> Main idea is that when rifts are young and have bordering mountains, most drainage is away from them, and only as rifts mature and their bordering mountains are eroded are regional master streams localized. Africa and the Red Sea provide models for this important idea.

Gallagher, K., and Brown, R., 1999, The Mesozoic denudation history of the Atlantic margins of southern Africa and southeast Brasil and their relationship to offshore sedimentation, in Cameron, N.R., Bate, R.H., and Clure, V.S., eds., The oil and gas habit of the South Atlantic: Geological Society [of London] Special Publication 153, p. 41–53.

> An important background paper that combines heat flow (present and past) with apatite fission track dating to estimate denudation rates and uplift, which are compared qualitatively with the preserved offshore record. Gallagher and Brown conclude that regional paleodrainage is the vital link. Compare with Winker (1982; cited in section on the Americas).

Garner, H.F., 1974, The origin of landscapes: London, Oxford University Press, 734 p.

A textbook on geomorphology with many references and examples of river systems throughout the world that are relatively unknown in much U.S. literature. Extensive bibliography of both U.S. and foreign literature and good line drawings.

Glock, H., 1931, The development of drainage systems: A synoptic view: Geographical Review, v. 21, p. 475–482.

An early paper describing the sequential stages of the evolution of drainage systems. Concentrates on development of tributaries — hence, birth of stream channels. Clearly recognizes three important processes in the evolution of a drainage system: extension (downslope), elongation (headward growth), and integration (adjustments and integration of tributaries). Unfortunately, these ideas were mostly ignored in the later geomorphic literature.

Golonka, Jan, Bocharova, N.Y., Ford, D., Edrich, M.E., Bednarczyk, J., and Wildharber, J., 2003, Paleogeographic reconstructions and basins development of the Arctic: Marine and Petroleum Geology, v. 20, p. 211-148.

> Thirty-one maps of plate positions around the Arctic Ocean for all the Phanerzoic. See also Ford and Golouka (2003). Important background reference.

Gorshkov, G., and Yakusheva, A., 1973, Physical geology (Fizicheskaya Geologiya): Moscow, MIR Publishers, 690 p.

> This is an introductory textbook on physical geology that presents a refreshingly different point of view and supplies examples and maps not found in American literature. For example, chapter 7 discusses river systems and their development, with emphasis on Europe and Asia.

Goudie, A., 2002, Great warm deserts of the world: Landscapes and evolution: Oxford, Oxford University Press, 44 p.

Easy-to-read, well-referenced, and well-illustrated (over 20 beautiful colored photographs) book is your source book for rivers and deserts. Summation of a lifelong work.

Hack, J.T., 1960, Interpretation of erosional topography in humid temperate regions: American Journal of Science, v. 258A (Bradley volume), p. 80–97.

> Rejects the theory of the geomorphic cycle (Davis) and proposes the concept of dynamic equilibrium as the basis for interpreting regional landscapes (graded rivers).

Hamblin, W.K., and Christiansen, E.H., 2004, The Earth's dynamic systems [10th ed.]: Upper Saddle River, N.J., Pearson-Prentice Hall Inc., 759 p.

Contains a rare textbook treatment of the modern characteristics of big river systems, their relation to plate tectonics, how their patterns are modified, and their ages (p. 330–333). Hamblin believes the principal control is tectonics, and that the slope of continents is away from one or more accretionary margins (see also Inman and Nordstrom, 1971).

Hauck, S.A., Phillips, R.J., and Maribeth, H., 1998, Venus crater distribution and plains and resurfacing models: Journal of Geophysical Research, Section E: Planets, v. 103, p. 13, 635–13, 642.

> Volcanic debris buries preexisting topography, so later channel systems start again on a uniformly level surface. This is a way to start a new cycle of erosion, in this case, bombardment from asteroids. See Potter (1978) for early discussion of how this applies to big rivers.

Holbrook, J., and Schumm, S.A., 1999, Geomorphic and sedimentary response of rivers to tectonic deformation:
A brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings: Tectonophysics, v. 305, p. 287–306.

Synthesis article, well summarized by its final Figure 8, which shows the response of an idealized river to different structural influences.

Howard, A.D., 1964, Drainage analysis in geologic interpretation: A summary: American Association of Petroleum Geologists Bulletin, v. 51, p. 2246–2259.

Classic, timeless fundamental paper — Figures 1 through 4 plus Table 1 give the complete story. Don't study rivers without this information. See also Melton (1959).

Huggett, R.J., 1994, Fluvialism or diluvialism? Changing views on super floods and landscape change: Progress in Physical Geography, v. 18, p. 335-342.

> Speculative background paper discusses how waves from extraterrestrial impacts in the ocean might affect river systems.

Inman, D.L., and Nordstrom, C.E., 1971, On the tectonic and morphologic classification of coasts: Journal of Geology, v. 79, p. 1–21.

The first to recognize that most large river systems drain to passive margins. Landmark paper.

Japsen, P., and Chalmers, J.A., 2000, Neogene uplift and tectonics around the north Atlantic: Overview: Global and Planetary Change, v. 24, p. 165-174.

> Figure 1 idenfifies areas of major Neogene uplift around the North Atlantic and summarizes all the methods used. There was also an earlier Paleogene uplift.

Korzhev, S.S., 1970, The principal divide of the Earth and common tendencies in the development of drainage networks of rivers (Glavnyi vodorazdel Zemli i obshchie tendentsii razvitiya rechnoi seti): Izvestia Academy Sciences USSR, Series Geography, 1970, No. 5, p. 5–16.

> Figure 1 divides the Earth into Pacific, Arctic, Atlantic, and Indian Ocean drainage, plus internal (arid to semiarid drainage). The present principle divide of the Earth runs across Eurasia-Africa from Angola to far eastern Siberia. Figure 1, a world map of drainage to the oceans, most useful.

Lane, F.C., 1949, Earth's grandest rivers: New York, Doubleday and Co., 305 p.

Discusses fluvial processes from a geography point of view and describes the great rivers of each continent. Excellent summary of how a geographer understood rivers 50 years ago and good summary of earlier geographic information.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964, Fluvial processes in geomorphology: San Francisco, W.H. Freeman, 522 p.

> "A river might better be thought of as having a heritage rather than an origin" (p. 421). The logic underlying this statement is that rivers continually accommodate themselves to tectonic and climatic changes, and hence thinking of them as having a clear beginning or end is rarely useful.

Long, D.G.F., 2004, Precambrian rivers, in Ericksson, P.G., Altermann, W., Nelson, D.R., Mueller, M.U., and Catuneau, O., eds., The Precambrian earth: tempos and events (Developments in Precambrian Geology, 12): Amsterdam, Elsevier, ch. 7.8, p. 660-663.

Rare short, but well referenced summary of Archean rivers emphasizes large sandy braid plain deposits along coastlines (with short feeding rivers?). Mudstones rare. Author suggests that major steps in the Earth's Precambrian development occurred in three "event clusters" at about 2.7, 2.2-1.8, and 0.8-0.6 Ga leaving open the question of what this means for big river systems.

Martonne, E., 1927, Regions of interior-basin drainage: Geographical Review, v. 17, p. 397–414.

> Pioneering paper gives numerical data for the areas of internal drainage for the entire globe and relates them to variations in latitude and the index of aridity. Concludes

that 27 percent of the land surface of the globe has internal drainage. Includes an excellent large-scale map showing (1) interior basin drainage, (2) areas without surface drainage, and (3) through-flowing drainage. Basis for possible conceptual map?

Melton, F.A, 1959, Aerial photographs and structural geomorphology: Journal of Geology, v. 67, p. 351-370.

Estimates (based largely on a mid-America experience) that 25 to 75 percent of all rivers in nonglacial areas are structurally controlled (Table I) — a resounding endorsement of the structural control of virtually all drainage (volcanism, glaciation, delta, and sand dunes excepted). Important paper.

Miall, A.D., 1981, Alluvial sedimentary basins: Tectonic setting and basin architecture, in Miall, A.D., ed., Sedimentation and tectonics in alluvial basins: Geological Association of Canada Special Paper 23, p. 1–33.

> Key background paper for the study of rivers in their lower courses relates drainage patterns and orientation to basin types and tectonics.

Miall, A.D., 1996, The geology of fluvial deposits: New York, Springer Verlag, 582 p.

Chapter 11, "Plate Tectonic Control of Alluvial Stratigraphy," is rich in both relevant ideas and illustrations (81 in all). Important source and synthesis of ideas focused on fluvial deposits with many implications for paleodrainage. See also Miall (1981).

Miall, A.D., and Gupta, A., eds., 1999, Varieties of fluvial form: New York, John Wiley and Sons, 521 p.

A collection of 21 papers, most of which describe the hydrology of smaller rivers, channel processes, and channel types. Some information on tectonic influences on river evolution is provided by the paper, "Drainage Evolution of the Sundays River, South Africa" (p. 145–166). Also discusses fluvial evolution in areas with volcanic and tectonic activity, such as the Armeria River, Mexico (p. 167–187). Especially interesting is the paper by S. Tooth, "Floodouts in Central Australia," p. 219–247, which provides information on how deserts begin to modify drainage patterns. Useful for understanding the Niger, Yellow, and Nile Rivers and drainage in Arabia and central Asia.

Mulder, T. and Syvitski, J.P.M., 1996, Climate and morphologic relationships of rivers: implications of sea-level fluctuations on river loads: Journal of Geology, v. 104, p. 509-523.

> This most significant paper contains empirical equations relating basin area to load, slope, and length. These are used to explore how sea-level fluctuations might affect rivers. Also of interest are Figure 6 (integrated drainage of France, England, and the Low Countries) and Figure 8 (European drainage if sea level were 200m lower).

National Geographic Society, 1984, Great rivers of the world: Washington, D.C., National Geographic Society, 448 p.

> A summary of the geographic characteristic of rivers. Most emphasis is on human interactions with rivers and how rivers have influenced culture and history.

Oberlander, T.M., 1984, Origin of drainage transverse to structures in orogens, in Morisawa, M., and Hack, J.T., eds., Tectonic geomorphology: Boston, Unwin Hyman, p. 155-181.

Argues that streams may erode their way across the transverse ridges of orogens (in addition to antecedence and superposition), as is evidenced by trellised drainage patterns within an orogen. Important process paper.

O'Connor, J.E., and Baker, V.C., 1992, Magnitudes and implications of peak discharges from glacial Lake Missoula: Geological Society of America Bulletin, v. 104, p. 267–279.

Estimates peak discharge at source of about 17 ± 3 million m³/s, and that flow may have lasted several days. See also Benn and Evans (1998, p. 343).

Ollier, C.D., 1991, A hypothesis about antecedent and reversed drainage: Geografia Fisica e Dinamica Quaternaria, v. 14, p. 243–246.

"It is here proposed that, if a tectonic obstacle is created across a major river, the river will respond by cutting an antecedent gorge. If a major river is reversed, it is by backtilting of the basin" (p. 243).

Ollier, Cliff, 1991, Ancient landforms: London and New York, Belhaven Press, 232p.

> This book of 14 chapters does not emphasize big rivers as such, but is rich in fundamentals and insights to big rivers and deserves much more attention. Many

informative illustrations from much of the world make this small book well worth reading.

Ollier, C.D., 1992, Global change and long-term geomorphology: Terra Nova, v. 4, p. 312–319.

> Argues that major rivers have time scales comparable to major tectonic features, regolith, and continental drift. Thought-provoking article.

Ollier, C.D., 1997, Geomorphology and mountain building: GeografiaFisicaeDinamicaQuaternaria(Supplemento), ser. 3, v. 3, p. 1–12 (Fourth International Conference on Geomorphology).

> Ollier believes most mountain ranges are eroded plateaus and thus separating post-planation structures (steep faults) from pre-planation structures (nappes and fold belts) is important. Also believes major rivers may be older than mountains. Totally new drainage unlikely to be found on passive margins. Major drainages have ages comparable to those of many global tectonic features, on the same scale as global tectonics (p. 10). Important paper by a long-term student of regolith, drainage, and landscape.

Ollier, C., and Pain, C., 2000, The origin of mountains: London and New York, Routledge, 345 p.

> A provocative book that argues that mountains are made by the erosion of uplifted plateaus. Chapter II on drainage and structure is most relevant.

Olson, R.E., 1970, A geography of water: Dubuque, Iowa, C. Brown Co., 132 p.

Short book on river geography. Chapter five presents a brief, but significant, description of selected large rivers.

Ouchi, S., 1985, Response of alluvial rivers to slow tectonic movement: Geological Society of America Bulletin 96, p. 504–515.

An experimental study addresses how river patterns change when they encounter transverse uplifts.

Owen, H.G., 1983, Atlas of continental displacement, 200 million years to the present: Cambridge, Cambridge University Press, 159 p.

> Seventy-six maps together with some brief discussions provide a good "hard copy" from which to analyze river evolution and continental drift.

Pavlis, T.L., Hamburger, M.W., and Pavlis, G.L., 1997, Erosional processes as a control on the structural evolution of an actively deforming fold and thrust belt: An example from the Pamir-Tien Shan region, central Asia: Tectonics, v. 16, p. 810–822.

> Pavlis et al. argue that river erosion plays an important role in tectonics (effects of erosion on tectonic transport and the mass balance). In this view, precipitation (climate) is key. As they write, "One need only look at deep canyons carved by rivers as an illustration of their power to denude the landscape, yet typically, we think of this process as a passive consequence of uplift. Moreover, because rivers are able to cut canyons across the grain of an uplifting orogen and in many cases even maintain entrenched meanders, we also tend to assume that rivers within an orogen cut downward only. In the Pamir region the evidence suggests that neither of these assumptions is necessarily valid. In this system the Surkhob River appears to play an active role in the structural process because the river's capacity to transfer sediment delivered by the thrust system in turn affects the mass balance that ultimately controls the style of deformation within the thrust system. Specifically, it appears that the river's ability to carry mass laterally from the system affects the accumulation of mass at the deformation front, and in so doing, this mass balance has a direct effect on the geometry of thrust systems as well as long-term exhumation within the orogen. Moreover, it appears that, over geologic time, the river has actually been pushed laterally by tectonic processes and has not simply cut downward to form a canyon" (p. 819-820.

Pazzaglia, F.J., Gardner, T.W., and Merritts, D.J., 1998, Bedrock fluvial incision and longitudinal profile development over geologic time scales determined by fluvial terraces, in Robinson, D.A., and Williams, R.B.G., eds., Rivers over rock: Fluvial processes in bedrock channels: American Geophysical Union, Geophysical Monograph 107, p. 207–235.

> Pazzaglia et al. believe that strongly concave river profiles have the stream power needed to keep up with uplift, whereas those that have straight or convex profiles do not (p. 231).

Potter, P.E., 1978, Significance and origin of big rivers: Journal of Geology, v. 86, p. 13-33.

Early effort to access the controls on big river systems and their significance for ancient deposits is good source of early references. Rand McNally, 1980, Encyclopedia of world rivers: London, Rand McNally, 231 p.

> Contains important geographic data on all the major rivers of the world, such as length, size of drainage basin, and distinctive characteristics, throughout its length. Excellent for basic background information.

Rodriguez, I.I., and Rinaldo, A., 1997, Fractal river basins — Chance and self-organization: Cambridge, Cambridge University Press, 547 p.

> A remarkable book in which the nature of river basins and their evolution is analyzed using fractal geometry. Short abstracts at the beginning of each chapter clearly describe the contents and main points. Main thrust is that river basin evolution produces network structures with fractal characteristics. Important chapters for the geologist include "A View of River Basins," "Fractal Characteristics of River Basins," "Self-Organized Fractal River Networks," "On Landscape Self-Organization," and "Geomorphologic Hydrologic Response."

Rzóska, J., 1978, On the nature of rivers: The Hague, Dr. W. Junk, 65 p.

Two parts — well-illustrated discussion of the geology, biology, and limnology of the Nile, Zaire, and Amazon Systems followed by a general discussion centered about the question "What is a river?" Strong emphasis on the biological aspect of rivers.

Sarnthein, M., 1978, Sand deserts during glacial maximum and climatic optimum: Nature, v. 272, p. 43-46

Sand dunes and deserts were much more widespread 18,000 years ago than today and covered 50 percent of the land between 30 degrees north and 30 degrees south, so that tropical rainforests and adjacent savannahs were greatly reduced to a narrow corridor. This agrees with the concept of ice-age aridity in the tropics.

Schumm, S.A., 1968, Speculations concerning paleohydrologic controls of terrestrial sedimentation: Geological Society of America Bulletin, v. 79, p. 1573–1588.

> Speculates on the effects of changing vegetation on erosion and river development as the Earth evolved — braided streams were in part supplemented by meandering ones when plants became widespread. Useful to remember when proposing universal laws for big river behavior. Big picture sedimentology.

Schumm, S.A., 1986, Alluvial river response to active tectonics, in Wallace, R.E., ed., Active tectonics: Washington, D.C., National Academy Press, p. 80-94.

Schumm argues that change in gradient caused by active tectonics affects aggradation, erosion, and river pattern. Evidence for this is based on Ouchi's (1985) studies and from the lower Mississippi valley — thus all short-term "2000 year" evidence is used rather than long-term geologic evidence.

Schumm, S.A., Dumont, J., and Holbrook, J., 2000, Active tectonics and alluvial rivers: Cambridge, Cambridge University Press, 290 p.

Four parts and 10 chapters provide broad overview plus good illustrations and references. Figures 6.9 and 6.13 provide good examples of how different reaches of a river can be summarized.

Schumm, S.A., and Ethridge, F.G., 1994, Origin, evolution and morphology of fluvial valleys, in Dalrymple, R.W., Boyd, R., Zaitlin, B.A., and Scholle, P.A., eds., Incised-valley systems: Origin and sedimentary sequences: Society for Sedimentary Geology, Special Publication 31, p. 11–27.

Good overview about valley formation. Background paper.

Scotese, C.R., 1997, Paleogeographic atlas: Arlington, University of Texas, Department of Geology, PALEOMAP Progress Report 90-0497, 45 p.

> Twenty-one pages of text include brief summaries of tools used to make paleogeographic maps, followed by a discussion of 20 maps, some of which are colored. Maps start in late Precambrian.

Selby, M.J., 1985, Earth's changing surface: Oxford, Clarendon Press, 607 p.

Chapter 17, "Ultimate Planation," discusses peneplains and erosion cycles — a topic relevant to the duration of big rivers and the conditions needed for their existence (see Figure 17.1).

Singleton, E., ed., 1908, Great rivers of the world as seen and described by famous writers: New York, Dodd and Mead Co., 358 p.

A fascinating description of rivers as seen through the eyes of many famous people, including some geologists. Although nonscientific, these descriptions provide interesting reading. Smith, A.G., 1999, Gondwana: Its shape, size, and position from Cambrian to Triassic times: Journal of African Earth Sciences, v. 28, p. 71–97.

> Figure 2 provides the first summation of the total area of all the scattered ports of Gondwana in all seven continents. Figure 2 is a basic map for understanding Eurasia drainage.

Snead, R.E., 1972, Atlas of world physical features: New York, John Wiley and Sons, 158 p.

Short section on rivers and drainage basins (p. 61-76) includes data on distribution of stream frequencies, interior drainage basins, length of rivers, deltas, and magnitude of sedimentary load.

Summerfield, M.A., 1991, Global geomorphology: Harlow, England, Longman Group, 537 p.

Chapter 16, "Tectonics and Drainage Development" (p. 405–431), is of general interest and discusses nearly all aspects, including passive margins, rifts, and Africa, although it does not address big rivers in geologic history. Highly recommended.

Summerfield, M.A., ed., 2000, Geomorphology and global tectonics: Chicester, John Wiley and Sons, 368 p.

Four parts and 16 chapters: chapter 1 gives a critical overview, chapter 3 considers coupled tectonic and surface processes, chapter 4 addresses fission track dating, chapter 5 discusses macro-scale processes of mountain-belt erosion, and the remaining 11 chapters are devoted to special areas of the world (interestingly, big rivers are not listed in the index and nowhere seem to be discussed).

Timofeev, D.A., 1965, The principal divide and development of drainage of the continents (Glavnye vodorazdely i razvitie gidroseti materikov): Doklady Instituta Geografii Sibiri i Dal'nego Vostoka (Institute of Geography of Siberia and Far East, Vladivostock), p. 29–37.

> Figure 2 divides the Earth's drainage into five parts: Arctic, Atlantic, Indian, Pacific, and interior. Three types of divides are recognized: close coincidence between maximum relief and limit of the watershed, approximate coincidence, and no coincidence (highest relief is distant from the limit. The last case suggests the rapid and recent extension of the watershed. Many additional observations are made.

Tooth, S., 2000, Process, form, and change in dry land rivers: A review of recent research: Earth-Science Reviews, v. 51, p. 67-107.

> Rivers in hyper-, arid-, semi-, and humid-arid climates have extreme variability, because rainfall is particularly sporadic. Figure 3, of the Sahara, is notable. Massive bibliography. Background paper for "drying up" of big rivers. Much emphasis on Australia.

Twidale, C.R., 1976, Analysis of landforms: Sidney, John Wiley and Sons (Australasia Pty. Ltd.), 572 p.

> A textbook on geomorphology. Much useful background data on fluvial processes, indirect effects of Late Cenozoic climatic changes on river systems, and an extensive bibliography.

Twidale, C.R., 1998, Antiquity of landforms: An "extremely unlikely" concept vindicated: Australian Journal of Earth Sciences, v. 45, p. 657–668.

> "African and Australian workers long ago concluded that paleoforms exist in contemporary scenery" (p. 657). Important philosophical paper rich in references old and new.

Twidale, C.R., 2004, River patterns and their meaning: Earth Science Reviews, v. 67, p. 159-218.

Comprehensive summary illustrated by 41 figures, many from Australia, provide the essentials for understanding patterns. Excellent.

Twidale, C.R., and Romani, V., Jr., 1994, The Pangaean inheritance: Cuaderno Laboratorio Xeolóxico de Laxe (Coruña), v. 19, p. 7–36.

Twidale and Romani argue that many of today's landforms are paleoforms that have survived from Pangea.

Veevers, J.J., and Tewari, R.C., 1995, Gondwana master basin of peninsular India between Tethys and the interior of the Gondwanaland Province of Pangaea: Geological Society America Memoir 187, 72 p.

> In our view, the best ever example of big thinking about paleo river systems. Figure 40 shows radial paleo drainage in the late Paleozoic away from the center of Antarctica as reconstructed from Australia, India and Africa.

Africa

Adamson, D., McEvedy, R., and Williams, M.A.J., 1993, Tectonic inheritance in the Nile Basin and adjacent areas, in Schick, A.P., ed., Surficial processes and landscape evolution; rift valleys and arid terrains: Israel Journal of Earth Sciences, v. 41, p. 75–85.

A summary of tectonic history, beginning with the Neoproterozoic, relates the Nile to fractures, faults, and basin development. See also Issawi and McCawley (1993).

Adamson, D.A., and Williams, F., 1980, Structural geology, tectonics, and control of drainage in the Nile Basin, in Williams, M.A.J., and Faure, H., eds., The Sahara and the Nile: Quaternary environments and prehistoric occupation in northern Africa: Rotterdam, Baldema, p. 225–252.

> The Nile drainage basin and the detailed courses of its tributaries were strongly influenced by structural features and tectonic events, but overall, the present course of the Nile is the result of Cenozoic rifting. Uplift, rifting, volcanism, and stream capture have caused continuous changes in the drainage patterns in its headwaters.

Almond, D.C., 1986, Tectonic and magmatic evolution of the Afro-Arabian Dome, in Nesbitt, R.W., and Nichol, I., eds., Geology in the real world — The Kingsley Dunham Volume: Institute of Mining and Metallurgy, London, p. 11–15.

Figure 1 shows the distribution of older and younger volcanic rocks around the Red Sea Rift, which Almond believes to have been only uplifted in the Pliocene rather than the Miocene.

Bosellini, A., 1989, The continental margins of Somalia; their structural evolution and sequence stratigraphy: Memorie di Scienze Geologiche/Universitá di Padova, v. 41, p. 373–458.

> This study provides a broad, in-depth overview of the evolution of the horn of Africa, starting with the tectonic development of the western Indian Ocean and Somalia, and the fracturing of Gondwana, followed by Karroo rifting. The memoir sets forth Cretaceous and Tertiary deposits, and in so doing shows how some of today's coastal wadis and rivers had their origin in the Oligocene-Miocene. Strongly recommended for an overview of this part of Africa.

Burke, K., 1996, The African Plate: Suid-Afrikaanse Tydskrif vir Geologie, v. 99, p. 341–409.

This long paper, prepared for the 24th du Toit Memorial Lecture, has 50 figures and provides an extended overview of the evolution of Africa in the last 30 Ma; includes discussion of paleodrainage. Many, many references.

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

> Burke and Wells believe that "radar river valleys" of northeastern Sudan were western tributaries of the ancestral Nile rather than part of a much longer trans-African river.

Cahen, L., 1954, Gélogie du Congo Belge: Musée Royal Congo Belge, Liège, 557 p.

Chapter 16 provides a detailed discussion of the stratigraphy of the Congo (Carboniferous to Holocene). Erosional surfaces and terraces ranging from Cretaceous to Quaternary are recognized along the major river valleys. The evolution of the Congo drainage systems involves a series of stream captures, whereas in the east, rifting and volcanism were major factors. Present drainage in the central and western Congo developed when a large Pliocene lake, which occupied the Congo Basin, was captured by headward erosion of a coastal stream. Four maps show segments of drainage developed during the various geologic episodes. Compare with Karner and Driscoll (1999) and Deffontaines and Chorowicz (1991).

Cheng, S., Deng, Q., Zhou, S., and Yang, G., 2002, Strath terraces of Jinshaan Canyon, Yellow River, and Quaternary tectonic movements of the Ordos Plateau, North China: Terra Nova, v. 14, p. 215–224.

Five periods of uplift, the oldest believed to be about 1.4 Ma, affected the interior of the Ordos Plateau, where it is cut by the Yellow River in its Jinshaan Canyon.

Cox, K.G., 1992, Karoo igneous activity, and the early stages of the break-up of Gondwanaland, in Storey, B.C., Alabaster, T., and Panhurst, R.J., eds., Magmatism and the causes of continental breakup: Geological Society [of London] Special Publication 68, p. 137–148.

This somewhat speculative paper relates regional centrifugal drainage in southeastern Africa to paleo-

hotspots (see also Cox's 1989 paper in Nature; cited in section on Background).

Deffontaines, B., and Chorowicz, J., 1991, Principles of drainage basin analysis from multisource data: Application to the structural analysis of the Zaire Basin: Tectonophysics, v. 194, p. 237–263.

> Simplified evolution of the Zaire Basin and significance of its drainage patterns are discussed on pages 257– 261 and illustrated in Figures 6 and 7. Notable for the strong tectonic control of the drainage network and the Bakongo aulacogen in its lower course. Good source of references on the Zaire Basin and on drainage analysis.

de Witt, M.C.J., Marshall, T.R., and Partridge, T.C., 2000, Fluvial deposits and drainage evolution, in Partridge, T.C., and Maud, R.R., eds., The Cenozoic of southern Africa: New York, Oxford University Press, p. 55–72.

> Cenozoic drainage of southern Africa has links backs to the Carboniferous because, as Karoo deposits were eroded, rivers were influenced by the structural grain of the long-lasting Proterozoic–late Carboniferous unconformity and by the position of the old Carboniferous ice divide. Figures 4-4 and 4-5 show drainage evolution and Table 4-1 gives the stratigraphy of related gravels.

Dingle, R.V., and Hendey, Q.B., 1984, Late Mesozoic and Tertiary sediment supply to the eastern Cape Basin (SE Atlantic) and paleodrainage systems in southwestern Africa: Marine Geology, v. 56, p. 13–26.

> Pioneer paper relates Mesozoic and Tertiary offshore deposits to drainage changes of the Orange River, which cuts through South Africa's long coastal escarpment to enter the South Atlantic. Two older transects of escarpment are recognized and believed to have occurred during low stands. Compare to Winker (1982).

Dixey, F., 1939, Some observations on the physiographic development of central and southern Africa: Transactions of the Geological Society of South Africa, v. 41, p. 113–171.

One of the few sources for an overview of the geomorphology of central and southern Africa has a summary of the origin of its river systems (p. 158–160). See also Dixey (1943, 1955).

Dixey, F., 1943, Erosion cycles in central and southern Africa: Transactions of the Geological Society of South Africa, v. 45, p. 151–181. "... The main drainage pattern was due originally to post-Karoo (Early to Middle Jurassic) deformation and faulting" (p. 175).

Dixey, F., 1955, Some aspects of the geomorphology of central and southern Africa: Geological Society of South Africa, annex to v. LVIII, 58 p.

This paper summarizes Dixey's lifelong interest in the regional geomorphology of southern Africa, gives his interpretation of the origin of the Zambezi River (p. 30–37) and the extent and age of Africa's notable erosion surfaces.

Dollar, E.S.J., 1998, Paleofluvial geomorphology in southern Africa: A review: Progress in Physical Geography, v. 22, p. 325–349.

Scholarly, thorough, well-illustrated review has over 220 references. Research of fluvial systems in southern Africa has two main objectives: diamond exploration and a broader, more academic interest in Cenozoic landscape and climatic evolution. Figure 4 illustrates backtilting of proto-Molopo drainage system by faulting.

Forbes, R., 1932, The desiccation problem in East Africa: The capture of the Souroby by the Black Volta: Geographical Review, v. 22, p. 97–106.

A fascinating paper on the effects of desertification on stream capture. Observations and discharge measurements show that the capture of the Black Volta is actually in progress and is undergoing drainage changes similar to that which occurred earlier for the Niger. Good model for the evolution of the Niger and the Yellow Rivers. See Talbot (1980).

Grove, A.T., 1970, The ancient erg of Hausaland, and similar formations on the south side of the Sahara: Geographical Journal, v. 124, pt. 4, p. 526–533.

> Ancient ergs in the Sahara indicate significant climatic shifts, presumably as the result of glacial and interglacial cycles. Deep weathering, stream erosion, and the formation of lakes occurred in humid periods and dunebuilding occurred in intervening arid periods. All had an important influence on evolution of drainage and relief.

Grove, A.T., and Warren, A., 1968, Quaternary landforms and climate on the south side of the Sahara: Geographical Journal, v. 134, p. 194–208.

Informative discussion and maps of the Senegal, middle Niger Valley, the Chad Basin, Sudanese Qoz, and the

Nile Valley during the Quaternary indicate alternating pluvial and dry periods, with a resulting shift of the Sahara limits over a distance of more than 500 km. These changes caused significant changes in the sub-Sahara drainage patterns and provide an important model of how expansion of deserts can change drainage systems.

Hospers, J., 1971, The geology of the Niger River area, in Delany, F.M., ed., Geology of the East Atlantic Continental Margin, v. 4, Africa: Institute of Geological Science, Report 70/16, p. 121–142.

> Brief discussion of the Pleistocene capture of the upper Sudanese Niger by the lower Niger during a Pleistocene pluvial. See Reijers et al. (1999) for the lower Niger.

Issawi, B., and McCauley, J.E., 1993, The Cenozoic landscape of Egypt and its river systems: Annals of the Geological Survey of Egypt, v.19, p. 357-384.

> Important, well-referenced and -illustrated paper argues that during the Cenozoic, Egypt was drained by three rivers systems — the Gulf (40 to 16 Ma), the Qena (24 to 6 Ma), and the Nile (6 to present) — and that the present Nile is composed of segments of all three. Compare with articles by Adamson et al. (1993) and Selley (1997).

Karner, G.D., and Driscoll, N.W., 1999, Tectonic and stratigraphic development of West Africa and eastern Brazilian margins: Insights from quantitative basin modeling, in Cameron, N.R., Bate R.H., and Clure, V.S., eds., The oil and gas habitats of the South Atlantic: Geological Society [of London] Special Publication 153, p. 11-40.

> Pages 29–33 relate offshore unconformities and facies to lateral migration (Congo, Africa) or to abrupt capture (San Francisco/Paraíba do Sul, Brazil) in the Tertiary. Knowledge of offshore stratigraphy facilitates the dating of such events. The Sao Francisco River is believed to have been captured in the Eocene, and the Congo started to migrate southward during the Late Cretaceous.

Lister, L.A., 1979, The geomorphic evolution of Zimbabwe, Rhodesia: Transactions of the Geological Society of South Africa, v. 82, p. 363-370.

Summarizes the six African erosional cycles and discusses the drainage evolution of the Zimbabwe and Limpopo Rivers.

Martin, H., 1975, Structural and paleogeographic evidence for an Upper Paleozoic sea between southern Africa and South America, in Campbell, K.S.W., ed., Gondwana geology: Canberra, Australian National University Press, p. 37–59.

Contains a map of Permian–Carboniferous glacially shaped valleys oriented westward toward South America.

McCauley, J.E., and Breed, C.S., 1993, Comparisons between the Nile River, Egypt and the Colorado River, USA, in Ulf, T., and Schandelmeier, H., eds., Geoscientific research in northeast Africa: Proceedings of the International Conference on Geoscientific Research, Northeast Africa: Rotterdam, Balkema, p. 723–726.

> The Nile and Colorado Rivers and their predecessors are believed to have much in common; both are exotic streams with asymmetrical tributaries, upper valleys are older than lower valleys, both have similar rim or plateau gravels, regional drainage reversals occurred early in their histories, major drops in sea level (due to plate tectonics) affected both, headward erosion and capture played important roles in their final stages of integration, and both are composite rivers composed of the surviving parts of older smaller rivers. See also Grabert (1978; cited in section on the Americas).

Michel, P., 1968, Genése et évolution de la vallée du Sénégal de Bakel á l'embouchure (Afrique occidentale): Zeitschrift für Geomorphologie, N.F., v. 12, p. 318-349.

About 500 km of the lower course of the Senegal is studied in detail (terraces mapped, longitudinal profiles, red dunes, flooded clay layer of Holocene estuary, etc.). Ancient dunes date from in late Wisconsin—a dry spell reduced flow and increased dune migration, so the river was stopped. Conversely, in pluvial times a new course may develop (p. 332–334).

Moore, A.E., and Larkin, P.A., 2001, Drainage evolution in south-central Africa since the breakup of Gondwana: South African Journal of Geology, v. 104, p. 47–68.

> Carefully documented (15 figures, subsurface data, space images, structure, and topography) and well-argued analysis of over 130 Ma of drainage evolution (post-Gondwana breakup) in southern Africa. Outstanding model to follow.

Moore, A., and Blenkinsop, T., 2002, The role of mantle plums in the development of continental scale drainage patterns: The southern Africa model revisited: South African Journal of Geology, v. 105, p. 353–360. Drainage evolution from Permian-Carboniferous to Early Cretaceous is summarized and broadly supports the idea of Cox (1989) that drainage is both radial down the flanks of the dome and also associated with the rifts that develop in a dome.

NEDECO, 1959, River studies and recommendations on improvements of Niger and Benue Rivers: The Hague, Netherlands Engineering Consultants, 1000 p.

> Geology, origin, and present topography discussed on p. 24–25. Diagram on Plate II 4.1.1-1 includes a rare longitudinal profile of the Niger River.

Nugent, C., 1990, The Zambezi River — tectonism, climatic change and drainage evolution: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 55–69.

> The upper and middle Zambesi River considered to be entirely separate river systems and only connected in recent times by overflowing of a large lake in the upper Zambezi region during the last interglacial period. Evidence is based on separate concaved upward longitudinal profiles of the two river segments and catastrophic flood deposits downstream. Subsequent drainage diversions are the product of rifting of the Chobe Graben and aggredation of the Chobe Swamps.

Partridge, T.C., 1998, Of diamonds, dinosaurs and diastrophism: 150 million years of landscape evolution in southern Africa: South African Journal of Geology; v. 101, p. 167–184.

> Upper Cretaceous drainage net of southern Africa is reconstructed in Figure 6. Also notable is Figure 13, a map of the African Superswell.

Partridge, T.C., and Maud, R.R., 1987, Geomorphic evolution of southern Africa since the Mesozoic: South African Journal of Geology, v. 90, p. 179–208.

> Discussion of all prior work ably summarized in Appendix A. Relates offshore sedimentation to erosion surfaces. Many detailed topographic cross sections. Remarkable paper!

Partridge, T.C., and Maud, R.R., 1988, The geomorphic evolution of southern Africa: A comparative review, in Dardis, G.F., and Moon, B.D., eds., Geomorphological Studies of Southern Africa: Proceedings, Symposium on the Geomorphology of Southern Africa/Transkei: Rotterdam, Balkema, p. 5–15.

Brief summary of their 1987 paper and a rebuttal to Dixey (1939, 1943, 1955).

Partridge, T.C., and Maud, R.P., eds., 2000, The Cenozoic of Southern Africa: Oxford Monographs of Geology and Geophysics 40, Oxford University Press, 406 p.

> Twenty-three wide-ranging chapters include two important for riverine studies: "Macro-Scale Geomorphic Evolution of South Africa" and "Fluvial Deposits and Drainage Evolution." Key regional reference.

Pritchard, J.M., 1979, Landform and landscape in Africa: London, Edward Arnold., 160 p.

> Pritchard believes that the major drainage patterns of Africa are strongly influenced by the "basin and swell" structure of the African continent. He presents a series of maps showing (1) the capture of Lake Aroriane (upper Niger) by the lower Niger, (2) the capture of Lake Congo by headward erosion of a coastal river, and (3) the capture of the upper Zambezi drainage (which once flowed westward into the Kalahari Basin). He argues that the Nile River dates from the Eocene and has undergone many changes during its long history, including the drainage of Lake Sudd. Compare with Issawi and McCauley (1993).

Reijers, T.J.A., Petters, S.W., and Nwajide, C.S., 1997, The Niger Delta Basin, in Selley, R.C., ed., African basins: Sedimentary basins of the world, 3: Amsterdam, Elsevier Publishing, p. 151–172.

> Basic references for the Benue and lower Niger, whose ancestors are traceable to the Early Cretaceous (Albian-Santonian) and the separation of South America from Africa. See also Hospers (1971) for the upper Niger.

Said, R., 1981, The geologic evolution of the River Nile: New York, Springer Verlag, 151 p.

Extensive treatment on the geology of the Nile with stratigraphic documentation of how the Nile River in Egypt evolved from the Miocene to the present in five distinct episodes. The Nile River is believed to have been in existence since the Late Miocene, since the result of the regression of the Mediterranean Sea and development of the Nile Canyon is the result of desiccation of the Mediterranean. During the Messinian event, a long canyon was cut upstream to the Asawn Dam and later uniquely flooded and partially filled with marine deposits (Fig. 65). The present Nile evolved from the Early Pliocene to the present. Said, R., 1994, Origin and evolution of the River Nile, in Howell, P.P., and Allan, J.A., eds., The Nile, sharing a scarce resource: Cambridge, Cambridge University Press, p. 17–26.

The Nile seems to have evolved by the interconnection of several independent basins and rivers (p. 17) — for example, the present Nile seems to be only about 10,000 years old (the result of a pluvial period), but its canyon in Egypt is of Miocene age. Four distinct sections recognized today. Concise, informative article condensed from earlier book. Compare with Issawi and McCauley (1993).

Selley, R.C., ed., 1997, African basins: Amsterdam, Elsevier Publications, 440 p.

Basic background reference linking modern rivers to the basins they cross is especially helpful for the Nile.

Summerfield, M.A., 1996, Tectonics, geology and long-term landscape development, in Adams, A.T., Goudie, A.S., and Ornie, A.R., eds., The physical geography of Africa: Oxford, Oxford University Press, p. 1–17.

> Clear, short, and incisive overview of Africa by a longterm student of the continent. Much use of regional geophysics to explain relief, rivers, and their evolution. Excellent article to start your study of Africa.

Talbot, M.R., 1980, Environmental responses to climate change in the west African Sahel over the past 20,000 years, in Williams, M.A.J., and Faure, H., eds., The Sahara and the Nile: Rotterdam, Balkema, p. 37–62.

Fascinating map of the watersheds of the combined Niger and Sengal Rivers.

Thomas, D.S.G., and Shaw, P.A., 1988, Late Cainozoic drainage evolution in the Zambezi Basin: Geomorphological evidence from the Kalahari Rim: Journal of African Earth Sciences, v. 7, p. 611–618.

Internal drainage of southern Africa captured by the lower Zambezi. Several informative maps.

Thomas, D.S.G., and Shaw, P.A., 1992, The Zambezi River; tectonism, climatic change and drainage evolution; is there really evidence for a catastrophic flood; discussion and reply: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 91, p. 175–182.

Thomas and Shaw argue against the idea that the two

graded profiles of the Zambezi are the result of rapid draining of a now-abandoned lake and believe that the Zambezi did not exist before the Pliocene. All earlier literature about the Zambezi cited.

Visser, J.N.J., 1987, The paleogeography of part of southern Gondwana during the Permo-Carboniferous glaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 61, p. 205–219.

Figure 6 shows preglacial drainage in much of southern Africa.

Visser, J.N.J., 1995, Post-glacial Permian stratigraphy and geography of southern and central Africa: Boundary conditions for climatic modeling: Paleogeography, Paleoclimatology, Palaeoecology, v. 118., p. 213v243.

> Important background paper to explain paleodrainage development of southern Africa and South America since the Permian (for example, a Congo Basin much like that of today is shown in Figure 4. Identifies ice cap centers (Fig. 6), gives portions of land covered by ice and water (Table 2), and has four paleogeographic maps (Figs. 7-10).

Wellington, J.H., 1958, The evolution of the Orange River Basin: Some outstanding problems: South African Geographical Society, v. 40, p. 3–30.

> Concludes that the Orange River was superimposed on a much thicker and more extensive sequence of Karoo rocks. Considers the possibility that the former Orange system may have been connected to the Limpopo and Zambezi Rivers.

Wendorf, F., and Schild, R., 1976, Prehistory of the Nile Valley: New York, Academic Press Inc., 403 p.

Emphasis on Quaternary to Holocene geology, with a large section on archeology.

Williams, M.A.J., and Faure, H., eds., 1979, The Sahara and the Nile: Rotterdam, Balkema, 607 p.

Excellent compilation of various papers written in both English and French. Part 2, "The Nile," is especially informative on the evolution of the Nile River in prehistoric times. The oldest silts deposited by the Nile are pre-Late Paleolithic.

Australia

Bishop, P., 1986, Horizontal stability of the Australian continental drainage divide in south-central New South Wales during the Cainozoic: Australian Journal of Earth Sciences, v. 33, p. 295–307.

> A study of the south-central Australian continental divide using dateable paleostream channels, especially valleys infilled by basalt flows. Concludes that the divide has not shifted horizontally at least from late Oligocene time and is not related to the formation of the Tasman Sea.

Brown, M.C., 1989, Structural and stratigraphic framework of groundwater occurrence and surface discharge in the Murray Basin, southeastern Australia: Journal of Australian Geology and Oceanography, v. 11, p. 127– 146.

> Large, but thin, basin contains Australia's longest river, the Murray-Darling, which flows from one passive margin to another. Beautiful color and black and white maps, some showing sequential filling. See also Brown and Stephenson (1989).

Brown, M.C., and Stephenson, A.E., 1989, Geology of Murray Basin, southeastern Australia: Australia Bureau of Mineral Resources, Record 5989/53, Gondwana Series 17, 422 p.

Fifteen chapters, seven appendices, 17 enclosures, 174 figures, and 45 tables set forth the geology of this vast, thin Tertiary basin and show that the Murray-Darling River had its origin in the Paleocene. Informative figures.

Gale, S.J., 1992, Long-term landscape evolution in Australia: Earth Surface Processes and Landforms, v.17, p. 323– 343.

> Australia has the world's oldest rocks and landscape, and the main features of Australia's landscape are said to be 107 to 108 years old — quite different than the idea that most of the world's landscape is Tertiary. Figure 5 shows the inception of drainage in Australia. Essential paper.

Hou, B., Frakes, L.A., Alley, N.F., and Clarke, J.D.A., 2003, Characteristics and evolution of the Tertiary paleovalleys in the northwest Gawler Craton, South Australia: Australian Journal of Earth Sciences, v. 50, p. 215-130.

Absolutely outstanding study of Tertiary paleovalley

evolution based on outcrop mapping, satellite imagery, and a wide variety of geophysical techniques (TEM, AEM, DEM, gravity and seismic reflection and refraction). Excellent model.

Langford, R.P., Wilford, G.E., Truswell, E.M., and Isern, A.R., 1995, Palaeogeographic atlas of Australia; v. 10, Cainizoic: Canberra, Australian Government Publishing Service, 37 p.

> Succinct text and beautiful continent-wide-colored maps show inferred paleodrainage over wide areas based on present physiography and Cainizoic deposits.

Nott, J.F., 1992, Long-term drainage evolution in the Shoalhaven catchment, southeast Australia: Earth-Surface Processes, v. 17, p. 361–374.

> Shoalhaven River Valley in southeast Australia contains pre-Eocene sediments that establish its present course throughout the Cenozoic and possibly even earlier. Long-term stability of big river systems is supported (see also Bishop, 1986).

Ollier, C.D., and Pain, C.F., 1994, Landscape evolution and tectonics in southeastern Australia: Journal of Australian Geology and Geophysics, v. 15, p. 335–345.

"Rivers flowing north and west across southeastern Australia are older than the formation of ... [its] eastern continental margin and the Murray basin" (p. 335). Figures 6 through 8 are informative and could be useful models.

Smith, T.L., 1960, The dead river systems of the Murumbidgee, New South Wales: Geographical Review, v. 50, p. 368– 389.

> Concludes that the Murrumbidgee River once built a huge floodplain with an alluvial fan system of distributaries. This large fan was 180 miles long and more than 80 miles wide, and its gradient was about 1 foot per mile. The fan was built during the Pleistocene as the sea receded to its present position.

Smith, T.L., 1982, T.L., 1982, The geomorphic history of the Australian desert: Striae, v. 17, p. 4–19.

> Provides history of the Australian desert, starting in the Cretaceous, and explains how ancient drainage is related to widespread erosion surfaces and some of its present drainage.

Stephenson, A.E., and Brown, C.M., 1989, The ancient Murray River system, in Brown, C.M., ed., Papers from Murray Basin 88, Geology, Groundwater and Salinity Management Conference: Journal of Australian Geology and Geophysics, v. 11, p. 367–395.

Excellent short summary of Brown (1989). Beautiful colored maps. Classic.

Stewart, A.J., Blake, D.H., and Ollier, C.D., 1986, Cambrian river terraces and ridge tops in central Australia: Oldest persisting landforms: Science, v. 233, p. 758–761.

> Paleovalleys filled with Middle Cambrian sediments were structurally controlled, and today's erosion has exhumed many of these valleys. Figure 2 is excellent.

Struckmeyer, H.I.M., and Totterdell, J.M., coordinators, 1990, Evolution of a continent: Canberra, Australia Bureau of Mineral Resources, 96 p.

A valuable series of 71 color paleogeographic maps, together with brief explanations, illustrate the evolution of Australia from Cambrian time to the present. Cretaceous and Cenozoic maps show how the present rivers evolved since the withdrawal of the last major marine transgression. Rivers in the western part of Australia were established some 55 Ma ago and are now represented by chains of playa lakes. River systems in the eastern part of the continent are also old, but the channels shifted across wide flat areas in the Gulf of Carpentaria, Lake Eyre, and the Murray Basin, depositing thin sheets of sand. Present river channels in eastern Australia evolved from these early alluvial systems.

Tooth, S., and Nauson, G.C., 1995, The geomorphology of Australia's fluvial systems: Retrospect, prospect, and program in physical geography: v. 19, p. 35–60.

Background paper suggests that stream systems in Australia differ somewhat from those of other continents.

Twidale, C.R., 1993, Gondwana (Late Jurassic and Cretaceous) palaeosurfaces of the Australian craton: Geomorphology, v. 112, p. 157–186.

Discussion of the Gondwana landscape (p. 178-179).

Twidale, C.R., 1997, Persistent and ancient rivers — Some Australian examples: Progress in Physical Geography, v. 18, p. 291–317. Broad review with many riverine references, mostly to Australia, but some to India, South America, and North America. Important paper summarizes paleodrainage in Australia.

Van de Graff, W.J.E., Crowe, R.W.A., Bunting, J.A., and Jackson, M.J., 1977, Relict Early Cainozoic drainages in arid western Australia: Zeitschrift Geomorphologie, N.F., v. 21, p. 379–400.

> Present-day playas, some of which are strongly linear, help mark the courses of a vast system of paleodrainage in arid western Australia. Stratigraphic and geomorphic evidence suggests a Late Cretaceous to Early Tertiary age for this paleodrainage. This study is a good example of how epeirogenic warping can change drainage pattern. Also gives details of what happens to a river when it drifts into an arid zone.

Wellman, P., 1987, Eastern Highlands of Australia; their uplift and erosion: Journal of Australian Geology and Geophysics, v. 10, p. 277–286.

> Wellman argues for semicontinuous river uplift and rapid downcutting. Uses basalt flows in valleys to date river and valley ages (Fig. 4).

Young, R., and MacDougall, I., 1993, Long-term landscape evolution: Early Miocene and modern rivers in southern New South Wales, Australia: Journal of Geology, v. 101, p. 35–49.

Basaltic lavas in Miocene and even in some Mesozoic valleys show that the Early Miocene landscape is largely preserved in these highlands, which form one of the world's great escarpments.

Eurasia

Abela, G., 1977, Morphologie und Entwicklung des Rheinsystems aus der Sicht des Mainzer Raumes, in Domrös, M., et al., eds., Festschrift zum 41 Deutschen Geographentag vom 30 Mai bis 12 Juni 1977 in Mainz: Geographisches Institut der Johannes Gutenberg-Universität, Mainz, p. 246–259.

> The Rhine is least as old as the Early Pliocene (p. 247). Figure 2 shows subsequent developments of drainage.

Alsdorf, D., Barazangi, M., Litak, R., Seber, D., Sawafi, T., and Al-Saad, D., 1995, The intraplate Euphrates Fault System-Palnyrides Mountain belt junction and relationship to Arabian Plate boundary tectonics: Annali de Geofisica, v. 38, p. 385–397.

Middle course of the Euphrates River in Syria overlies a graben that formed in the latest Cretaceous.

Alvarez, W., 1973, Ancient course of the Tiber River near Rome: An introduction to the Middle Pleistocene volcanic stratigraphy of central Italy: Geological Society of America Bulletin, v. 84, p. 749–758.

> Volcanic tuffs in the Late Pliocene or Early Pleistocene formed a lake and diverted the ancestral Tiber through a col into its present course. Good summary of the local Italian literature and an example of how volcanism can influence drainage.

Andres, W., 1989, The central German upland: Catena Supplement 15, p. 23-44.

This summary of the history and development of the relief of the central German uplands (Rheinisches Schiefergeberge) states that the Rhine probably first crossed these mountains during the Late Miocene (p. 31).

Auffret, J.P., Alduc, D., Larsonneur, S., and Smith, A.J., 1980, Cartographie du réseau de paléovallées et de l'épaisseur des formations superficielles meubles de la Manche orientale: Annales l'Institute Océanographique, v. 56, p. 21–35.

> Shows a complex anastomosing channel pattern under La Manche (English Channel) draining to the southwest; compare with Lautridou et al. (1999).

Barbour, G.B., 1936, Physiographic history of the Yangtze: Geographical Journal, v. 87, p. 2–34.

> This paper, based on a 1934 excursion (including aerial overviews,) argues for the capture of the Upper Red by the Yangtze in either the Early Pleistocene or Late Pliocene. Supporting evidence includes low cols between their drainages, barbed tributaries, sharp elbows of capture, and the correlation of col elevations with elevations of mature topography (p. 30). The Three Gorges are discussed. Good source of earlier literature.

Barsuk, O.A., 1974, On the structural pattern of the Lena drainage system (Lena River) east Siberia: Bolletin, Society Naturalistes of Moscow (Biulleteni Moskovskogo abschestva ispytatelei prirody, otdel geologicheskii), v. 49, p. 159. Barsuk believes the Lena River to date from the latest Jurassic or Early Cretaceous — the youngest pre Quaternary rocks in its watershed — and that the locations of most of its tributaries are strongly controlled by structure.

Berendsen, H.J.A., and Stouthhamer, E., 2001, Palaeogeographic development of the Rhine–Meuse Delta, the Nederlands: Geography/Utrecht University (Koninklijke Van Gorcum, Assen), 268 p.

> This book is a good example of a specific, detailed study rich in far-ranging significance for deltaic sedimentation. From our point of view, however, Figure 2.2 tells the complete story—the paleographic evolution of the Rhine-Meuse Delta since its beginnings in the Miocene. Eleven chapters, five appendices, and three addenda.

Bessereau, G., Guillocheau, F., and Huc, A.Y., 1995, Source rock occurrence in a sequence stratigraphic framework: The example of the Lias of the Paris Basin, in Huc, A.Y., ed., Paleogeography, paleoclimate and source rocks: American Association of Petroleum Geologists Studies in Geology v. 40, p. 273–301.

Figure 1 is a simplified geologic map of central and western France and shows the pronounced structural control of the Seine River between the Amorican and Ardennes Blocks, but only partial control of the Loire River. Compare with Perrondon and Zabek (1990).

Bijlsma, S., 1981, Fluvial sedimentation from the Fennoscandian area into the North-West European Basin during the Late Cenozoic, in Van Loon, A.J., ed., Quaternary geology: a farewell to A.J. Wiggers: Geologie en Mijnbouw, v. 60, p. 337-345.

> This river system (Miocene to Early Pleistocene) flowed across the Netherlands, Denmark, Germany, and Poland and is inferred primarily from deposits of gray to white mature sands, Miocene brown coals, clay and rounded quartz gravel plus some silicified limestones (the Baltic Gravel Assemblage).

Boenigk, W., 1982, Der Einfluss des Rheingraben Systems auf die Flussgestchicte des Rheins: Zeitschrift Geomorphologie, N.F., Supplemental Band 42, p. 167–175.

The Rhine River started when the sea withdrew from the Rhine Graben at the end of the Early Miocene.

Brookfield, M.E., 1998, The evolution of the great river systems of southern Asia during the Cenozoic-India-Asia

collision: Rivers draining southwards: Geomorphology, v. 22, p. 285-312.

Remarkable paper for both its geographic scope and insight into broad regional geology shows that only some 10 Ma ago Southeast Asia's major drainages were completely different from those of today. Use of semilog profiles notable. Notes evidences for many river captures (p. 299) and that lines of lakes and dry valleys indicate former rivers in the dry, high Tibetian Plateau (p. 300). Persistence of knickpoints noted. Pioneering paper rich in both ideas and references.

Burbank, D.W., Beck, R.A., and Mulder, T., 1996, The Himalayan foreland basin, in Yin, A., and Harrison, T.M., eds., The tectonic evolution of Asia: Cambridge, Cambridge University Press, p. 149–188.

> Uppermost segments of Indus River first drained eastward as tributaries to the Ganges before being captured by the Indus in the Late Miocene(?). Excellent illustrations of the world's largest foreland basin.

Chang'an, L., Hongfu, Y., and Yan, Z., 1999, A study of the uplifting age of the central mountain ranges of China and its environmental effects, in Proceedings, International Association of Geologists, Yangtze Fluvial Conference, Shanghai, China: Shanghai, College of Resources and Environmental Science, East China Normal University, p. 85–86.

> Chang'an et al. believe that most of the Qinghai-Tibet Plateau was uplifted in the Early Pleistocene and that the upper and longest segment of the Yangtze River in the plateau dates from this time and closely follows structure down to the Three Gorges area near Yichang, the beginning of China's great alluvial plan.

Cheng, S., Deng, Q., Zhou, S., and Yang, G., 2002, Strath terraces of Jinshaan Canyon, Yellow River, and Quaternary tectonic movements of the Ordos Plateau, North China: Terra Nova, v. 14, p. 215–224.

Five periods of uplift, the oldest believed to be about 1.4 Ma, affected the interior of the Ordos Plateau, where it is cut by the Yellow River in the Jinshaan Canyon.

Cheng, Z., Ruichun, X., and Shimei, W., 1997, The special long reversed river section in the Yangtze River reaches: Geology and Mineral Resources of South China, Technical Report 3, p. 33–38 (English summary).

Cheng et al. argue that barbed tributaries show about

2000 km of the Yangtze to have been reversed in its course east of Three Gorges, as a result of the India-Asia collision — a totally fantastic idea? Evidence cited includes barbed tributaries, wind gaps, and terrace elevations.

Clark, M.K., House, M.A., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang, X., and Tang, W., 2005, Late Cenozoic uplift of southestern Tibet: Geology, v. 33, p. 525-528.

Low-temperature thermochronometers show slow cooling between 100 to 10 to 20 Ma followed by rapid cooling starting at 13 Ma. These changes correlate with vegetation changes. Together this evidence points to rapid river entrenchment in eastern Tibet between 13 to 9 Ma ago.

Clark, M.K., Schoenbohm, L.M., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang, X., Tang, W., Wang, E. and Chen, L., 2004, Surface uplift tectonics, and erosion of eastern Tibet from large-scale drainage patterns: Tectonics, v. 23, (TC 1006), 20 p.

> Authors argue that a single, large southward flowing river drained the eastern great bend of the Himalayas before the Miocene and that uplift-related capture and reversal caused the change. Well documented with many references.

Clift, P.D., 2002, A brief history of the Indus River, in Clift, P.D., Kroon, D., Gaedicke, C., and Craig, I., eds., The tectonic and climatic evolution of the Aratan Sea region: Geological Society, Special Publication 195, p. 237-258.

The Indus seems to have been established close to its present course since about 18 Ma. Well referenced and contains a useful table of the sediment volumes of the offshore basins of southeastern Asia.

Clift, P.D., Shimizu, N., Layne, G.D., Blusztajn, J.S., Gaedicke, C., Schlüeter, H.-U., Clark, M.K., and Amjad, S., 2001, Development of the Indus Fan and its significance for the erosional history of the western Himalayas and Karahoram: Geological Society of America Bulletin, v. 113, p. 1039–1051.

Lead isotopes, sandstone petrology, and regional geology both on and offshore date the Indus Fan from about 55 Ma.

Clift, P.D., Amjad, S., Blusztan, J.S., Clark, M.K., Gaedicke, C., Layne, G.D., Schlueter, H.K., and Shimizu, N. 2000, Fifty-five million years of Tibetian evolution recorded in the Indus Fan: EOS, Transactions of the American Geophysical Union, v. 81, no. 25, p. 277–281.

New seismic and provenance data suggest that the Indus River and its fan system was initiated shortly after the India-Asia collision 55 million years ago; i.e., in the Early Eocene. The Indus River has remained in the suture zone for a period of some 55 million years after it first flowed through the area and demonstrates how difficult it is to stop or reroute a major river once it is established. Compare with Lindsay et al. (1991).

Coward, M.P., Dewey, J., Hampton, M., and Holroyd, J., 2003, Tectonic evolution, in Evans, D., et al., eds., The millennium atlas: Petroleum geology of the central and northern North Sea: Geological Society [of London], chapter 2, p. 17–33.

This chapter provides the tectonic overview to this splendid atlas of the North Sea. The view of this chapter is very broad — from basement through the Pleistocene — with global paleogeographic maps ranging over half the world. Hence, chapter 2 provides the foundation of insights to Late Paleozoic to modern river systems in western Eurasia.

Crasquim, S., Coordinator, 2000, Atlas Peri-Tethys, Explanatory Notes: UNESCO (CGM/CCGW), Paris, 286 p.

> Most useful for its Cretaceous and Tertiary maps of the dynamic area between the western Mediterranean Sea into Central Asia and the Middle East.

De Celles, P.G., Gehrels, G.E., Quade, J., and Oijha, T.P., 1998, Eocene–Miocene foreland basin: Development and the history of Himalayan thrusting, western and central Nepal: Tectonics, v.17, p. 741–765.

Sedimentology (paleocurrents and environmental analysis), petrology, and U-Pb ages of detrital zircons all indicate (Fig. 7) that until the Middle Miocene (Lower–Middle Siwalik Group) most of the Himalyan foreland basin drained into the Indus Fan. Compare with Schroder (1993) and Lindsay et al. (1991).

Delvin, W.J., Cogswell, J.M., Gaskins, G.M., Isaksen, G.H., Pitcher, D.M., Puls, D.P., Stanley, K.O., Wall, G.R.T., South Caspian Basin: Young, cool and full of promise: GSA Today, v. 9, No. 7, p. 1-9.

> Easy accessable, well written summary of geology and evolution of the South Caspian Basin is guide for Tertiary drainage development in this important region.

De Ruiter, R.S.C., Lovelock, P.E.R., and Nabulsi, N., 1995, The Euphrates Graben of eastern Syria: A new petroleum province in the northern Middle East, in Al-Husseini, M.I, ed., Selected Middle East papers from the Middle East Geoscience Conference, Geo '94: Manama, Bahrain, Gulf PetroLink, v. 1, p. 357–368.

Good documentation of a graben underlying the middle course of the Euphrates River in Syria (Fig. 9).

Dewey, J.F., Cande, S., and Pittman, W.C., III, 1989, Tectonic evolution of the India-Eurasia collision zone: Ecologae Geologica Helvita, v. 82, p. 717–734.

Dewey et al. suggest that about 250 km of eastern extrusion of the convergent zone and about 1000 km of crustral shortening has occurred since about 45 Ma — two key facts for the origin of the region's rivers.

Drachev, S.S., Savostin, L.A., Groshev, V.G., and Bruni, I.E., 1993, Structure and geology of the continental shelf of the Laptev Sea, eastern Russian Arctic: Tectonophysics, v. 289, p. 357–393.

> Figure 6 summarizes effectively the tectonic history of the Laptev Sea since the Maastrichian, the onset of rifting, and identifies four subsequent tectonic reorganizations. Basic for much Siberian drainage.Földvary, G.Z., 1988, Geology of the Carpathian Region: Singapore, World Scientific, 571p.

> The wide Hungarian Plain began to develop in the Miocene, especially in the Late Miocene–Early Pliocene (Pannonian-age sea) with great subsidence, thick (4000 m), and rapid sedimentation and a connection to the sea through the present Iron Gate. This sea gradually became a lake, presumably filled by the Danube, which followed a topographic low across the Iron Gate (p. 398–399, 504–506).

Frisch, W., Brügel, A., Dunkl, I., Kuhlemann, J., and Satir, M., 1999, Post-collisional, large-scale extension and mountain uplift in the eastern Alps, in Gosso, G., Jadoul, F., Sella, M., and Spalla, M.I., eds., 3rd Workshop on Alpine Geological Studies: Memorie di Scienze Geologiches, Universite di Padova, v. 51, p. 3–23.

> Volumes and ages of principal depocenters for eastern Alps in the last 34 Ma summarized in Figures 14 and 15. Figures 16 and 17 exceptional, because they combine source rock distribution with paleorelief based upon fission track dating. Pioneering paper. Compare with Kuhlemann et al. (2000).

Gabris, G., 1994, Pleistocene evolution of the Danube in the Carpathian Basin: Terra Nova, v. 6, p. 495-501.

> The history of the middle section of the Danube Rivers begins with the last marine regression from the Carpathian Basin. Initially, a pattern of river channels and lakes developed. As the lakes were filled with sediment, the Danube drainage developed connections with previously isolated basins. Thus, the evolution of the Danube has been controlled primarily by tectonic activity. Terrace formation has been influenced mainly by Pleistocene climatic fluctuations.

Garfunkel, Z., 1988, The pre-Quaternary geology of Israel, in Yorn-Tou, Y., and Tchermov, E., eds., The zoogeography of Israel: Dordrecht, Dr. W. Junk Publishers, Dordrecht, p. 7–34.

> The Jordan River of Israel and Syria follows the leftlateral Dead Sea Transform Fault, which formed in the Miocene, and thus created its initial relief. Probably the Jordan River dates from the Pliocene after a brief Pliocene marine ingression (p. 27–29).

Gibbard, P.L., 1995, The formation of the Straits of Dover, in Preece, R.C., ed., Island Britain: A Quaternary perspective: Geological Society [of London] S1pecial Publication 96, p. 15-26.

Figures 2 through 4 outline the paleogeography of the southern North Sea and English Channel prior to, during, and just after the last Elsterian/Anglian glaciation, and show how the Thames, Rhine, Somme, and Seine all flowed southwest after a glacial lake overtopped a divide at the Straits of Dover.

Gibbard, P.L., 1988, The history of the great northwest European Rivers during the past three million years: Royal Society of London, Philosophical Transactions Series B, v. 318, p. 559-602.

> An excellent summary of the origin of the present Elbe, Saale, Weser, Rhine, Meuse, Scheldt, Thames, Somme, and Seine Rivers (all late Miocene) as well as the former Baltic and Channel River systems. Earlier these rivers occupied shallow valleys and transported small amounts of mature detritus. Important paper with a most valuable and massive reference list.

Glennie, K.W., and Evans, G., 1976, A reconnaissance of the recent sediments of the Ranns of Kutch, India: Sedimentology, v. 23, p. 625-647. Glennie and Evans believe that much of the sediment of the Ranns was derived from the Indus and Nara Rivers, which used to flow into the eastern arm of the Great Rann. The River Sutlej, which now flows into the Indus, once flowed into the Nar. Similarly, the Jumna, before it was captured by the Ganges, once joined the Chautang. The Ghaggar and Saravati also flowed into the Nara.

Godard, G., Chevalier, M., Bouton, P., and Mouroux, B., 1994, Un fleuve yprésien du Berry a la Vendée, temoin de l'évolution paléogéographique et tectonique du Centre-Ouest de la France au Cénozoique: Geologie de la France, No. 4, p. 35-56 (English abstract).

> A Cenozoic river system more than 200 km long is reconstructed from deposits, subsurface geology, and topography, using palynology to establish dating. This river system predated the present Loire River, but was bisected (Fig. 8) by the uplift of the Vendée Hills and related faults in the late Lutetian (distal Pyrenean Orogeny). Many references.

Goff, J.C., Joues, R.W., and Horbury, A.D., 1994, Cenozoic basin evolution of the northern part of the Arabian Plate and its control on hydrocarbon habitat, in Al-Husseini, M.I., ed., Geo '94, The Middle East petroleum geosciences, v. 1, Selected Middle East papers from the Middle East Geoscience Conferences, April 25–27: Manama, Bahrain, Geo Petro Link, p. 402–412.

Background maps and essential text to explain the Tigris-Euphrates Rivers and Jordan River. See also Grabowski and Norton (1994) of the same volume and compare interpretations.

Görür, N., 1989, Timing of opening of the Black Sea: Sedimentological evidence from the Rhodope-Pontide fragment, in Sengör, A.M.C., ed., Tectonic evolution of the Tethyan Region: NATO Advanced Study Institute on Tectonic Evolution of the Tethyan Region 1985 (Istanbul Technical University), p. 131–136.

> Black Sea started as a back-arc basin with the beginning of subduction of the Tethyan ocean — in Jurassic Neocomian time when the northern shores of the Black Sea dipped south on an Atlantic-type continental margin. Rifting started in the Aptian to Cenomanian. Background paper for understanding the greater Middle East and southern Russia.

Grabowski, G.J., Jr., and Norton, I.O., 1994, Tectonic controls on the stratigraphic architecture and hydrocarbon systems of the Arabian Plate, in Al-Husseini, M.I, ed., Geo '94, The Middle East Petroleum Geosciences, v. 1, Selected Middle East Papers from the Middle East Geoscience Conference: Manama, Bahrain, Gulf Petro Link, p. 413–430.

Basic paleogeographic evolution in the Jurassic and Triassic. Figure 1 is excellent.

Grosswald, M.G., 1998, New approach to ice age paleohydrology of northern Eurasia, in Benito, G., et al., eds., Palaeohydrology and environmental change: Chichester, John Wiley, p. 199–214.

> Well-written article with five figures provides an overview of how the last northern hemisphere ice sheet (the late Weichselian) drastically altered the drainage of northern Eurasia causing rivers to flow, via shifting channels and Late Quaternary lakes, mostly into the Mediterranean. Proglacial drainage systems were vast, quite different than those of today, and included proglacial lakes, major spillways, and outbursts of icedammed lakes plus loess deposits, ice-rafted marine deposits, and freshwater plumes over the ocean (Figs. 15.1 and 15.5). Good source of Russian literature.

Gunnell, Y., Gallagher, K., Carter, A., Widdowson, M., and Hurford, A.J., 2003, Denudation history of the continental margin of western peninsular India since the early Mesozoic-reconciling apatite-fission track data with geomorphology: Earth and Planetary Letters, v. 215, p. 187-201.

A technical paper about the best choice for initial apatite fission track length shows that, when the standard length (16.3 um) was used, maximum denudation rates of Indian's western high escarpment greatly increased since about 50 Ma.

Hongzhen, W., Chief, 1985, Atlas of the palaeogeography of China: Wuhan, Institute of Geology, Chinese Academy of Sciences (Cartographic Publishing house, Beijing, China), p. 1-28 (English summary).

System-by-system summary of paleogeography for all of China.

Huh, Y., Tsoi, M.-Y., Zaitsev, A., and Edmond, J.M., 1998, The fluvial geochemistry of the rivers draining eastern Siberia: III. Tributaries of the Lena River draining the sedimentary platform of the Siberian Craton: Geochimica et Cosmochimica Acta, v. 62, p. 1657–1676.

On p. 1558-1660 is a brief summary of the geology and

origin of the Lena River, which is considered by the Russians to be an ancient antecedent stream traceable via stratigraphy and facies analyses back to the early Precambrian.

Hutchison, C.S., 1989, Geological evolution of Southeast Asia: Oxford, Clarendon Press, 368 p.

> Excellent for overall background, but only on p. 67–69 is drainage discussed. Figure 3.3 shows the Mekong abruptly changing course from south to southeast at Chiang Rai, where it abruptly turns southeastward near the Nanuttaradit Suture. The same map also shows the delta of the Red River (boundary of Vietnam and China) to be bordered by the Song Ma Suture.

Illies, J.H., and Baumann, H., 1982, Crustal dynamics and morphodynamics of the Western European Rift System: Zeitschrift für Geomorphologie, Suppemental Band 42, p. 135–165.

> Regional map covering Switzerland to the North Sea shows the Rhine Graben to be intercepted by the Rhenish Shield; the Rhine River closely follows the Rhine Graben into the North Sea Graben (see also Fig. 4.35 of Selby, 1985; cited in section on Background).

Jijun, L., and Shiyou, X., 1999, Uplift of the Qing-Tibet Plateau and the geomorphic evolution of the upper reach of the Yangtze River (focusing on the Three Gorges): Proceedings, International Association of Geologists Yangtze Fluvial Conference: College of Resources and Environmental Science, East China Normal University, Shanghai, China, p. 16–17.

Six erosion surfaces in the 150-km-long Three Gorge area suggest that the gorge was formed by an ancestral Yangtze River at least 2 Ma ago.

Kheirov, M.B., and Khalilov, N.Y., 1990, History of sedimentation from Oligocene to Quaternary in the central part of the middle Caspian Sea (Razvitiye osadkonakopleniya v Oligotsen-Chetvertichnoye vremya v tsentral'nol chasti Srednego Kaspia): Akademia Nauk Azerbaydzhanskoy SSR (Academy of Science of Azerbaijan SSR, Baku), v. 6, p. 6–11.

> Paleogeologic maps of the middle part of the Caspian Sea identify the presence of the ancestral Volga River as early as the Paleocene.

Koronovsky, Nikolai, 2002, 1 Tectonics and geology, in Shahgedanova, M., ed., The physical geography of northern Eurasia: Oxford, Oxford University Press, p. 1-35.

Overview of northern Eurasia's tectonic setting.

Korzhev, S.S., 1956, Reconstruction of the hydraulic network and the age of the divide between the Pacific and Arctic Oceans (O perestroike gidrograficheskoi seti i molodosti glavnogo vodorazdela mezhdu Tikhim i Severnym Ledovitym Okeanami): Izvestiya Akademii Nauk USSR, Seriya Geographia (Izvestiya Academy of Sciences of USSR, Series Geography), 1956, no. 1, p. 53–68.

> Detailed discussion of how the divide between part of the Lena and Amur watersheds has shifted toward the Pacific Ocean (but just the opposite of what one would expect?).

Kuhlemann, J., Frisch, W., Dunbel, B., Szekely, B., and Spiegal, C., 2000, Miocene shifts of the drainage divide in the Alps and their foreland basin: Zeitschriift Geomorphologie, N.F., v. 44, p. 103–138.

The watersheds of the western and southern Alps are reconstructed since Oligocene time; Figure 4 shows the progressive positions of thrust fronts in central Europe during the Tertiary, and Figure 5 (a-k) is a remarkable series of maps that combine drainage divides, river systems, and recycled and accumulated sediment volumes since the Oligocene. Key paper for the Rhine and Rhone and rivers.

Lacassin, R., Replumaz, A., and Leloup, P.H., 1998, Hairpin river loops and slip-sense inversion on Southeast Asian strike-slip faults: Geology, v. 26, p. 703–706.

> Abrupt changes in course can be caused by slip on leftand right-lateral faults. Both contemporary and fossil leftand right-lateral slip are seen on faults with large rivers in the Golden Triangle of Southeast Asia, suggesting that these rivers have an age of at least 5 Ma.

Lautridou, J.-P., Auffret, J.P., Baltzer, A., Clet, M., Lécolle, F., Lefebre, D., Lericolais, G., Roblin-Jouve, A., Balesca, S., Carpentier, G., Descombes, J.C., Oechiett, S., and Rousseau, D.-D., 1999, Le fleuve Seine, le fleuve Manche: Bulletin Société Géologique de France, v. 170, p. 545–558.

> Fluvial marine sands (Sables de Lozere) deposited on the plateau of the Paris Basin suggest that the history of the Seine Rive began at least during the Pliocene with uplift of surrounding massifs. The first entrenchment

of the river began 1 million years ago, as indicated by dated volcanic material eroded from the Massif Central. Subsequent history of the Seine and associated rivers is recorded in a complex terrace system associated with Pleistocene glaciation. The onshore Seine connects with a paleochannel system under the Manche. See also Auffret et al. (1980), Smith (1985), and Perrodon and Zabek (1990).

Li, J., Xie, S., and Kuang, M., 2001, Geomorphic evolution of the Yangtze Gorges and the time of their formation: Geomorphology, v. 41, p. 125–135.

> The Three Gorges occur between the upper rocky entrenched valley of the Yangtze and its lower alluvial valley. In the Gorges, local relief is about 2000 m and includes planation surfaces and seven terraces. Using both paleomagnetism and electrospin resonance (ESR), Li et al. date well-defined erosion surfaces and terraces and conclude that the Yangtze River is probably of Pliocene age.

Lin, A., Yang, Z., Sun, Z., and Yang, T., 2001, How and when did the Yellow River develop its square bend?: Geology, v. 29, p. 951–954.

> Outstanding example of tectonic controls of large rivers: Miocene-Pliocene accelerated movement of India against Asia diverted an earlier Eocene Yellow into an unusual rectangular pattern.

Lindsay, J.F., Holliday, D.W., and Hulbert, A.G., 1991, Sequence stratigraphy and the evolution of the Ganges-Brahmaputra Delta Complex: American Association of Petroleum Geologists Bulletin, v. 75, p. 1233–1254.

Seismic stratigraphy shows three stages in the development of the Ganges-Brahmaputra Delta: a protodelta (126–49.5 Ma) supplied by a small catchment after initial breakup at 126 Ma; a transitional delta started at 49 Ma with sedimentation greatly increasing at about 40 Ma; and finally, the modern delta developed (10.5 Ma–present). Detritus from the modern delta is derived from highlands and transported as far as 10°S via the Bengal deep-sea fan. Silt dominates the modern delta. This study provides an outstanding example of how erosional history can be reconstructed from subsurface deposits. Figure 21 is exceptional, and gives a clear graphic history.

Litak, R.K., Barazangi, M., Brew, G., Sawaf, T., Al-Inam, A., and Al-Youssef, W., 1998, Structure and evolution of the petroliferous Euphrates Graben System, southeast Syria: American Association of Petroleum Geologists Bulletin, v. 82, p. 1173–1190.

Good correspondence between fault system (aborted continental rift), river orientation, and thickness (Figs. 5.4–5.5).

Matoshko, A.V., Gozhik, P.F., and Ivchenko, A.S., 2002, The fluvial archive of the middle and lower Dnieper (a review): Netherlands Journal of Geosciences/Geologie en Mijnbouw, v. 81, p. 339–355.

The Dnieper watershed originated during the Late Miocene. The middle part of the valley has a broad alluvial basin whereas the lower part has a canyon (ending in an offshore delta?).

Neppel, F., Somogyi, S., and Domokos, M., 1999, Paleogeography of the Danube and its catchment, part 2: Budapest Water Resources Centre, 62 p.

> Twenty-one informative figures and 11 large color plates provide a comprehensive paleogeographic evolution of the Danube Basin since the Middle Miocene. Also included is a basinwide correlation table; much information on terrace systems, insights into the complex tectonic evolution of the basin, plus historical maps of the political evolution of the basin since 1774. In sum, the origin of the Danube is traceable back to the Middle Miocene, but the present system came into existence only in the Early and Middle Phocene, perhaps by lakes overfilling the low divide of the Iron Gate. Many freshwater lakes and swamps, as well as narrow marine embayments, all played important roles in the post-Middle Miocene evolution of the Danube. See Fink (1965), cited in Neppel et al. (1999), for an earlier summary.

Ollier, C.D., and Taylor, D., 1988, Reply: Major geomorphic features of the Koscivsko-Bega region: Journal of Australian Geology and Geophysics, v. 11, p. 125.

Figure 1 shows diversion of volcanic drainage around Mount Etna, Sicily.

Ori, G.G., 1993, Continental depositional systems of the Quaternary of the Po Plain (northern Italy): Sedimentary Geology, v. 83, p. 1–14.

Figure 1 provides an excellent plate tectonic interpretation of the Po River Basin — here called a molasse foredeep.

Perrodon, A., and Zabek, J., 1990, Paris Basin, in Leighton, M.W., Kolata, K.R., Oltz, D.F., Eidel, J.J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 632–679.

> Well-documented summary of structural and depositional history of the Paris Basin indicates that this intracratonic basin attained its present shape only during the Early Tertiary, when bordering massifs were uplifted (p. 658– 659). Compare with Pomeral (1978) and Lautridou et al. (1999).

Peterson, J.A., and Clarke, J.W., 1991, Geology and hydrocarbon habitat of the West Siberian Basin: American Association of Petroleum Geologists Studies in Geology 32, 96 p.

The Ob River occupies most of the Mesozoic–Tertiary West Siberian Basin; geology is well summarized by more than 50 paleogeographic maps, which show that the Ob had ancestors going back to the Middle Jurassic, but only in the Oligocene did it approach its present form. If only every major river had such information! Extensive Russian literature translated and compiled by Clarke.

Pomerol, C., 1978, Évolution paléogéographique et structurale du Bassin de Paris de Précambrien a l'actuel en relation avec les regions avoisinantes: Geologie en Mijnbouw, v. 57, p. 533-543.

> This paper takes a long view of the Paris Basin and suggests that it developed over a late Precambrian rift. Figure 1 shows a structural grain in the basement parallel to the lower course of the Seine River. Compare to Perrodon and Zabek (1990) and Lautridou et al. (1999).

Quitzow, H.W., 1975, Das Rheintal und sein Entstehung: Bestandsaufnamhe und Versuch einer Synthese, in Macar, P., ed., L'Evolution Quaternaire des bassins fluviaux de la Mer du Nord meridionale: Liége, Centenaire Société Géologique Belge, p. 53–104.

> Broad overview includes stream capture, tectonics, and structural controls for European rivers draining to the North Sea. Especially notable are Figure 1 (illustrates the ages of the different parts of the Rhine Systems) and Figure 4 (a remarkable longitudinal profile of the Rhine from the delta into the Alps). The Rhine formed in the Middle Miocene. Remarkable study. See also summary by Louis (1976, in Zeitschrift für Geomorphologie, v. 20, p. 124–127.

Reynolds, A.D., Simmons, M.D., Bowman, M.B.J., Brayshaw,
A.C., Ali-Zade, A. A., Guliyev, I.S., Suleymanova,
S.F., Ateava, E.Z., Mamedova, D.N., Koshkarly, R.O.,
1998, Implications of outcrop geology for reservoirs of
the Neogene Productive Series: Aspheron Peninsula,
Azerbaijan: American Association of Petroleum
Geologists Bulletin, v. 82, p. 25-49.

Facies mapping of outcrops establishes the late Miocene age of the ancestral Volga.

Rodionov, N.T., 1974, The history of development of the Lena River (K istorii razvitiya Sredney Leny): Geofologia (Geomorphology), 1974, no. 3, p. 94–100

First evidences of the Lena recognized in the Mesozoic (Cretaceous?), but principal formation believed to have been in the Paleocene. Subprovinces of middle course recognized, and there is some discussion of underlying bedrock, which includes extensive karst.

Royden, L.H., and Báldi, T., 1988, Early Cenozoic tectonics and paleogeography of the Pannonian and surrounding regions, in Royden, L.H., and Horowitz, Ferenc, eds., The Pannonian Basin: American Association of Petroleum Geologists Memoir 45, p. 1–16.

> The Pannonian Basin (most of present Hungary and parts of bordering regions) had marine deposits until the end of the Miocene when a lake developed, which was later filled by up to 7000 m of fluvial deposits (p. 14). Fundamental reference for the middle and lower Danube. See also Földvary (1988).

Sarnthein, M., 1972, Sediments and history of the postglacial transgression in the Persian Gulf and northwest Gulf of Oman: Marine Geology, v. 12, p. 245–266.

> Sedimentology indicates that the Persian Gulf was an arid land during the Pleistocene, that the ancestral Tigris and Euphrates Rivers flowed into an estuary, and no true delta was formed. Includes a paleographic map showing the Persian Gulf at various times during the transgression.

Schroder, J.F., Jr., 1993, Himalayas to the sea: Geomorphology and Quaternary of Pakistan in the regional context, in Schroder, J.F., Jr., ed., Himalayas to the sea: London and New York, Routledge, p. 1–42.

Overview of Indus River and its tributaries (p. 6–8) suggests the Indus existed as long as 20 Ma ago. Figure 1.3 shows clear deflection around the Raikot Fault, and Figure 1.7 shows bordering landslides. Schroder

suggests that large landslides may divert mountainous rivers. Much of the book, however, is devoted to Holocene and Pleistocene history.

Seeber, L., and Gornitz, V., 1983, River profiles along the Himalayan Arc as indicators of active tectonics: Tectonophysics, v. 92, p. 335–367.

> Important paper compares different tectonic models of the Himalayas with its transverse river gradients using the Hack method. Key idea is that the drainage pattern of a river "contains unique information about past and present tectonic regimes" (p. 343). Discussion of antecedence versus capture for drainage anomalies of the Himalayas north of their topographic divide most relevant; Seeber and Gornitz conclude that the south-flowing drainage of the Himalayas is antecedent (see p. 356 for many literature references to this problem, some dating back to 1968). Useful comparison is made with New Guinea (p. 358–362), and Seeber and Gornitz conclude that the relief and drainage of the two regions show the same response to subduction, but at different stages.

Sengör, A.M.C., Altiner, D., Cin, A., Ustaömer, T., and Hsü, K.J., 1988, Origin and assembly of the Tethyside orogenic collage at the expense of Gondwanaland, in Audley-Charles, M.G., and Hallam, A., eds., Gondwana and Tethys: Geological Society [of London], Oxford University Press, p. 119–181.

> Rich in maps and almost 300 references, this paper describes the structures produced as Gondwana collided with Asia. Sengör et al. believe that strike-slip faults with hundreds of kilometers of displacement are the most significant structures produced by this collision (and commonly, we add, these are followed by rivers).

Sissingh, W., 1998, Comparative Tertiary stratigraphy of the Rhine Graben, Bresse Graben and Molasse Basin: Correlation of Alpine foreland events: Tectonophysics, v. 300, p. 249–284.

> Figure 19 is a correlation table of Alpine tectonic activity and its relation to the Molasse Flysh Basin and the Rhine and Bresse (Rhone) Grabens. The Rhine Graben started filling in the Mid-Miocene and the Bresse in the Upper Miocene (thus the ages of the Rhine and Rhone Rivers). Similarity of sequences in the Molasse Foreland Basin and the two grabens suggest universal controls — when continents are under compression we have regression and when large grabens develop (tension) we have transgression (p. 280).
Smith, A.J., 1985, A catastrophic origin for the paleovalley systems of the English Channel: Marine Geology, v. 64, p. 65–75.

> Smith argues that the paleovalleys of the English Channel were formed by a catastrophic Pleistocene flood. Figure 1 a fine example of an anastomosing river system. See Auffret et al. (1980).

Songqiao, Zhao, 1986, Physical geography of China: Beijing, Science Press/New York, John Wiley & Sons, 209p.

Fourteen chapters and many maps plus 13 pages of colored plates. Attributes most topographic evolution to Miocene plate convergence and underthrusting (p. 11). Most useful is Chapter 3, "Geomorphological Features of China."

Srivastava, K.N, 1982, Evolution of drainage system of Himalayas: Geological Survey of India Miscellaneous Publication 41-3, p. 331–338.

> Srivastava proposes that initial Paleocene uplift resulting from continental collision was near the present divide between Arctic and Indian Ocean drainage (Angara land) and that antecedent rivers developed over subsequent uplift to the south. Five schematic plates. Compare with Brookfield (1998).

Ufimtsev, G.F., 1972, The position of the principle divide in interior and eastern Asia (Polojenie glavnogo vodorazdela vo Vnutrennei i vostochnoi Azii): Izvestia Academy Sciences USSR, Series Geografia, 1972 N.S., v. 5, p. 86–92.

Elaborates on Timofeev's 1965 paper (cited in section on Background).

Ufimtsev, G.F., 2002, Morphotectonics of Eurasia (Morfotektonika Evrazii): Irkutsk, Irkutsk University (Lithospheric Institute, Siberian Affiliate, Russian Academy of Science), 493p.

This treatise begins with an overview (relief of basement, platforms, and youngest fold belts) followed by much detail beginning in the Jurassic – the starting point of Eurasia's present relief (break up of Gondwana). The relief of Eurasia and its origins discussed in terms of 70 subheadings. Background material for Eurasian rivers. See also Ufimtsev (2001).

Ufimtsev, G.F., 2001, Tectonic relief of Eurasia: Geografia Fisica e Dinamica Quaternaria, v. 24, pl. 85-98. A single handed effort to summarize the geomorphic and tectonic zones of Eurasia, the worlds largest and most complex continent. Figures 1, 2, and 11 especially valuable.

Varnavskiy, V.G., Krillova, G.L., Krapiventseva, V.V., and Kuqnetsov, V.Y., 1992, Characteristics of lithologicstructural associations of complexes of the sedimentary basins: Petroleum Geology, v. 27, p. 9–35, 71–89, 141– 154.

> These are a valuable series of papers (translated from the Russian) on the Mesozoic basins of the Russian Far East with useful correlation tables. Lower course of Amur River overlies Miocene deposits. Translations by James Clarke.

Veevers, J.J., and Tewari, R.C., 1995, Gondwana master basin of peninsular India between Tethys and the interior of Gondwanaland, province of Pangea: Geological Society of America Memoir 187,72 p.

A basic reference for understanding Gondwanan paleogeography, this text outlines the radial drainage of the supercontinent away from the Gamburtser Mountains in east Antarctica (p. 48–49, Figs. 40–41, and especially Table 8). Important reference.

Velichko, A., and Spasskaya, I., 2003, Climate change and the development of landscapes, in Shahgedanova, M., ed., The physical geography of northern Eurasia: Oxford, Oxford University Press, p. 36–69.

> Best short summary in English of drainage evolution in northern Eurasia (p. 46–50). Stresses the importance of Miocene uplift and reorganization of river systems. Well referenced.

Wager, L.R., 1937, The Arun River drainage pattern and the rise of the Himalayas: Geographical Journal, v. 89, p. 239-250.

> Remarkable description and analysis of how the Arum River abruptly changes its eastward course from a wide, open valley in soft schists to a narrow, south-trending valley cut in granites. Wager believes the course of the Arum River was antecedent to the rise of the Himalayas. Striking photographs and many early references.

Wang, E., Burchfiel, B.C., Royden, L.H., Liangzhong, C., Jishe, C., Wenxin, L., and Zhiliang, C., 1998, Late Cenozoic Xianshuihe-Xiaojiang, Red River, and Dali Fault Systems of southwestern Sichuan and central Yunnan, China: Geological Society of America Special Paper 327, 108 p.

Detailed discussion of the complex evolution of part of South China reveals that the Red River Fault has rightlateral displacement, is over 800 km long, older than Pliocene age, and that the Red River closely follows it for great distances. Figure 29A is informative, and Figure 45 shows a 3 km offset by the Jinsha River (a tributary to the Red) where it crosses a fault. Rich source of control of shear faults on rivers and pull-apart basins.

Wang, H., 1985, Atlas of the paleogeography of China: Beijing, Institute of Geology, Chinese Academy of Science, Wuhan College of Geology Cartographic Publishing House, Beijing, 143 p.

Absolutely essential for eastern Asia.

Widdowson, M., and Cox, K.G, 1996. Uplift and erosional history of the Deccan Traps, India: Evidence from laterites and drainage patterns of the western Ghats and Konkan Coast: Earth and Planetary Science Letters, v. 137, p. 57–69.

> The western Ghats Escarpment originally formed from rifting and breakup of Pangea, which initiated the eastflowing drainage pattern on the upper Deccan Traps with a much smaller and shorter drainage system along the coast toward the new ocean. Did the coastal Serra do Mar Escarpment of Brazil form in the same way?

Yin, A., and Harrison, M., 1996, The tectonic evolution of Asia: Cambridge, Cambridge University Press, 666 p.

> Has five parts and 21 chapters, of which "Evolution of the Himalayas," "Himalayan Foreland Basin," "Red River Shear Zone in Yunan and Vietnam," and "Paleotectonics of Asia" are the most useful for regional drainage development. On the east side of the Himalayas, strike-slip faults are estimated to move as much as 10 to 20 mm a year. The Red River Shear Zone is believed to be a strike-slip fault with offsets up to 80 km or more. Indochina was squeezed to the southeast as India collided with Asia. Background paper.

Yin, A., and Nie, S., 1996, A Phanerozoic palinspastic reconstruction of China and its neighboring regions, in Yin, A., and Harrison, M., eds., The tectonic evolution of China: Cambridge, Cambridge University Press, p. 442–485.

Background for a better understanding of the evolution of China's rivers.

Yu, H., 1999, Age of Huang He Delta in continental shelf of Yellow Sea and Bahai Bay: Dizhi Lixue (Journal of Geomechanics), v. 5, p. 80–88.

There are two different opinions for the age of the Yellow River — pre-Tertiary or Pleistocene? Yu argues that there is only a post-Wisconsin delta of the Yellow River and therefore the age is Pleistocene.

Zagwijn, W.H., 1974, Paleogeographic evolution of the Nederlands during the Quaternary: Geologie en Mijnbouw, v. 53, p. 369–385.

Figures 1 and 2 show the Rhine in the Netherlands localized by a graben system.

Zhao, C., Xu, R., and Wang, S., 1997, The special long reversed river section in the Yangtze (Changjian) River reaches: Geology and Mineral Resources of South China, v. 3, p. 33–38.

From Xiangxi in Hubei Province to Shigw, some 2000 km, the Yangtze is said to be reversed, as judged by barbed tributaries, reversed terraces, and wind gaps. This reversal is believed to have occurred 150,000 to 200,000 years ago as the result of the Indian-Asia collision.

Zhukovskii, Y.S., 1967, Certain paleogeographic problems along the lower Lena River (O nekotorych voprosakh paleogeografii Nizhney Leny): Izvestia Vsesoiuznogo Geograficheskogo Obshchestva, v. 90, p. 56–63.

The lower Lena occupies a sag between the Sıberian Craton and the Verkhoyansk Collision Belt and seems to be as old as at least Early Cretaceous.

Ziegler, P.A., 1990, Geological atlas of Western and Central Europe [2nd ed.]: Bath, Geological Society [of London] Publishing House, 249 p.

Basic for Tertiary rivers systems in Europe.

Ziegler, M.A., 2001, Late Permian to Holocene paleofacies evolution of the Arabia plate and its hydrocarbon occurrences: GeoArabia, v. 6, p. 445-504.

> Provides overview of Arabian plate (with colored maps) and an in depth reference list through the Miocene with some information on the Holocene.

Zonenshain, L.P., Kuzmin, M.I., and Natapov, L.P., 1990, Geology of the USSR: A plate tectonic synthesis: American Geophysical Union, Geodynamic Series, v. 21, 234 p. Only a brief mention on p. 25–26 of Lena River — thought to be possibly Paleozoic in origin — but provides a good overview of how Asiatic Russia was put together.

The Americas

Ager, T.A., Matthews, J.V., Jr., and Yeend, W., 1994, Pliocene terrace gravels of the ancestral Yukon River near Circle, Alaska: Palynology, paleobotany, paleoenvironmental reconstruction and regional correlation: Quaternary International, v. 22/23, p. 185–206.

Ancestral Yukon gravels are possibly Early to Middle Pliocene.

Archer, A.W., and Greb, S.F., 1995, An Amazon-scale drainage system in the Early Pennsylvanian of central North America: Journal of Geology, v. 103, p. 611–628.

> Paleodrainge at the Mississippian-Pennsylvanian unconformity of eastern and central United States is broadly comparable to that of the present Amazon River system. One of the few direct modern-ancient riverine comparisons. See also Mann and Thomas (1968).

Baker, V.C., 1983, Late-Pleistocene fluvial systems, in Wright, H.E., Jr., and Porter, S.C., eds., Late-Quaternary environments of the United States — The Late Pleistocene, v. 1: Minneapolis, University of Minnesota Press, p. 113–128.

General background article, especially useful for the effects of catastrophic floods on river systems.

Belcher, R.C., 1975, The geomorphic evolution of the Rio Grande: Baylor Geological Studies Bulletin, v. 29, 64 p.

> Detailed summary of complex history uses Cretaceous and Tertiary stratigraphy, tectonics, and paleogeography, along with distribution of Late Tertiary-Pleistocene gravels, to arrive at a synthesis (p. 49–50). Well recommended and deserving of much wider readership.

Bemerguy, R.L., and Costa, J.B.S., 1991, Consideracões sobre a evolução do Sistima de drenagem da Amazônia e sua relação com o arcbouço tectônico-estructural: Boletim do Museu Paranense Emílio Goeldi, Ser. Ciencias de Terra, v. 3, p. 75-97.

A structural interpretation of the watershed of the Amazon river basin identifies a Permian divide (Purus

Arch) in mid section followed by later integrated drainage in the Miocene with latest adjustments in the Pliocene. A hidden paper well worth reading. English abstract.

Carlson, P.R., and Nelson, C.H., 1987, Marine geology and resource potential of Cascadia Basin, in Scholl D.W., Grantz, A., and Vedder, J.G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins — Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 523–535.

> Figure 2 shows the Astoria Channel and a base-ofcontinental slope valley offshore from the mouth of the Columbia River.

Cole, M.R., and Armentrout, J.M., 1979, Neogene paleogeography of the western United States, in Armentrout, J.M., et al., eds., Cenozoic paleogeography of the western United States: Pacific Coast Paleogeography Symposium 3, Pacific Section Society of Economic Paleontologists and Mineralogists, Los Angeles, p. 279–323.

> "The Cenozoic geology of western North America formed around a framework of Paleozoic and Mesozoic plutonic and metamorphic terrains" (p. 298). Miocene and Pliocene paleogeographic maps of California, Nevada, Washington, Oregon, and adjacent parts of Idaho, Utah, and Arizona (Figs. 2–3) display river systems, fans, deltas, basins, and elements of the landscape. Most impressive.

Colman, S.M., Halka, J.P., Hobbs, C.H., III, Mixon, R.B., and Foster, D.S., 1990, Ancient channels beneath Chesapeake Bay and Delmarva Peninsula: Geological Society of America Bulletin, v. 102, p. 1268–1279.

Three paleochannel systems, 2 to 4 km wide and incised 40 to 50 m, occur under Chesapeake Bay; all are ancient channels of the Susquehanna River with ages ranging from about 18 ka to perhaps 200 to 400 ka.

Costa, J.B.S., Hasui, Y., Borges, M. da Silva, and Bemerguy, R.L., 1995, Arcabouço tectônico Mesozóico-Cenozóico da região da Calha do Rio Amazonas: Geociênces, Sao Paulo, v. 14, p. 77–103.

Aggressive tectonic interpretation of the course of the Amazon and its tributaries — many different intervals and directions of stress inferred since the opening of the South Atlantic Ocean.

Costa, J.B.S., Bemerguy, R.L., Hasui, Y., and Borges, M.S., 2001, Tectonics and paleogeography along the Amazon River: Journal South American Earth Sciences, V. 14, p. 335-347.

> This paper sets forth the tectonic features that control the Amazon River as it flows across the Amazon Basin, a distance of about 1500 km. Normal and strike-slip faults control the orientation of many tributaries and parts of the main stream of the river. Reversal of Amazon noted in the Miocene.

Cousineau, P.A., and Longuépée, H., 2003, Lower Paleozoic configuration of the Quebec reentrant based on improved along-strike paleogeography: Canadian Journal of Earth Sciences, v. 40, p. 207-219

> In spite of multiple glaciations, both the Ottaway and Saquenay Rivers of Quebec follow topographic lows above Cambro-Ordovician grabens (Fig. 1).

Coward, M.P., Purdy, E.G., Ries, A.C., and Smith, D.G., 1999, The distribution of petroleum reserves in basins of the South Atlantic margins, in Cameron, N.R., et al., eds., The oil and gas habitats of the South Atlantic Ocean: Geological Society [of London] Special Publication 153, p. 101-131.

Key background paper with summaries of basins and rocks.

Davis, G.H., and Green, J.H., 1962, Structural control of interior drainage, southern San Joaquin Valley, California, in Short papers in geology, hydrology, and topography articles 120-179: U.S. Geological Survey Professional Paper 450-D, Article 146, p. D89–D91.

> The Kings River was abruptly diverted to and terminates in the Tulare Lake bed above a subsurface low filled with blue, black, and green clays and silts. Excellent example of a river ending in a small tectonic low now occupied by a lake in a semi-arid region.

De Rezende, W.M., 1972, Post Paleozoic geotectonics of South America related to plate tectonics and continental drift: Sociedade Brasileira de Geologia Anais do XXVI Congreso Brasileira Geologia, p. 205–210.

The first to think continent-wide about continental drainage and fracture systems. De Rezende suggested that the Amazon, Paraná, and other major tributaries all follow megafractures. Truly a pioneering paper.

Díaz de Gamero, M.L., 1996, The changing course of the Orinoco River during the Neogene: A review: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 123, p. 385–402.

> Pioneering article for South America, because it combines both subsurface off- and onshore information with tectonics to detail the history of the Orinoco River and its predecessors. Excellent source of information for northern South America. Compare with Potter (1997).

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lindin, E.R., McKittrich, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039.

Figures 11 and 12 outline paleoslopes and paleodrainages among Laramide sedimentary basins, mostly ponded. Remarkable synthesis covering a large area. Compare Figure 12 of this paper with Figure 13 of Brookfield (1998).

Duk-Rodkin, A., 1994, Tertiary-Quaternary drainage of the preglacial Mackenzie Basin: Quaternary International, v. 22-23, p. 221-241.

> Prior to glaciation, the present Mackenzie consisted of three rivers — one draining to Hudson Bay and two to the Arctic (Fig. 2). Figure 16 shows master paleodrainage. Classic example of glacial reorientation of regional drainage.

Duk-Rodkin, A., Barendregt., R.W., White, J.M., and Singhroy, V.H., 2001, Geologic evolution of the Yukon River: Implications for placer gold: Quaternary International, v. 82, p. 5–31.

Three stages of the Yukon are recognized: pre-Late Miocene, Early Pliocene, and drainage after the earliest Pliocene glaciations. Figure 2 is a rare comparison of present and paleodrainages and Figure 13 shows longitudinal profiles.

Duque-Caro, H., 1979, Major structural elements and evolution of northwestern Colombia, in Watkins., J.S., et al., eds., Geological and geophysical investigations of continental margins: American Association of Petroleum Geologists Memoir 29, p. 329–351.

> Delta of Magdalena is first recognized in Miocene-Pliocene. See Diaz de Gamero (1996, p. 399).

Eisbacher, G.H., Carrigy, M.A., and Campbell, R.B., 1974, Paleodrainage pattern and late orogenic basins of the Canadian Cordillera, in Dickinson, W.R., ed., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 143–166.

> Using the Himalayas as their modern example, Eisbacher et al. propose three canons of river evolution for orogens (p. 145–146): thrust faults separate erosional from depositional watersheds, drainage within mountains is mainly longitudinal, and major rivers are localized at frontal basins and reentrants.

Eyles, N., Arnaud, E., Scheidegger, A.E., and Eyles, C.H., 1997, Bedrock jointing and geomorphology in southwestern Ontario, Canada: An example of tectonic predesign: Geomorphology, v. 19, p. 17–34.

> Channel location and orientation cut into the lower Paleozoic (mostly carbonate) bedrock of Ontario are closely dependent on joint pattern, as is much postglacial drainage. Paper illustrates well small-scale tectonic control. Excellent.

Galloway, W.E., Ganey-Curry, P., Xiang, L., and Butler, R.J., 2000, Cenozoic depositional history of the Gulf of Mexico Basin: American Association of Petroleum Geologists Bulletin, v. 84, p. 1743–1774.

The ancestral delta of the Rio Grande River along the Texas-Mexico border has existed since the Paleocene, but was best developed during the Oligocene and Lower Miocene (Fig. 19). See also Belcher (1975) and McKenna (1997).

Garner, H.F., 1967, Rivers in the making: Scientific American, v. 216, p. 84–94.

Garner compares the drainage pattern of the Orinoco River and its tributary, the Caroni River (South America), to the pattern of the Channel Scablands, and believes the pattern is due to climatic change. He concludes that such drainage is a stage in the evolution of rivers.

Goulding, M., Barthem, R., and Ferrena, E., 2003, The Smithsonian atlas of the Amazon: Washington and London, Smithsonian Books, 253 p.

> This perceptive and beautifully illustrated book provides the most complete photographic field trip of all the river basins in the world. In addition, its text is clear and perceptive and a model for us all. Notable features include 60 maps; many new color photographs, some 250 references in English, Portuguese, and Spanish as

well as a complete index. Spanning Andean headwaters to the muddy coasts of the Guyanas, this is our candidate for the most useful and remarkable book ever published on a big river.

Grabert, H., 1967, Sobre o desaquamento natural da sistima fluvial do Rio Madera desde o construção dos Andes: Atas Simposio sobre a Biota Amazonica, v. 1 (Geociencias), p. 209–214.

The first paper to outline on a map the pre-Andean watershed of the Amazon system.

Grabert, H., 1978, Orinoco und Amazonas — Eine Betrachtung zum Alter beider Stromsysteme: Sonderveröffenlichungen des Geologischen Instituts der Universität Köln, v. 33, p. 179–191.

The history of both river systems is summarized in a concise table. Excellent model for anyone comparing and contrasting river systems.

Hawkings, T.J., and Hatfield, W.G., 1975, The regional setting of the Taglu Field, in Yorath, C.J., Parker, E.R., and Glass, D.J., eds., Canada's continental margins and off shore petroleum potential: Canadian Society of Petroleum Geologists Memoir 4, p. 633–662.

> Well-illustrated study shows downdip development of ancestral MacKenzie Delta in Neogene before Pleistocene glaciation. See also Duk-Rodkin (1994). Good example of importance of offshore geology for understanding onshore river history.

Hoorn, C., 1994, An environmental reconstruction of the ancestral Amazon River system (Middle–Late Miocene, NW Amazonia): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 112, p. 187–238.

> Identifies the oldest relics of the Amazon River generated by the uplift of the Andes in Middle to Late Miocene time in the Marañon Basin of Peru. Study integrates sedimentology and palynology with paleogeography. Classic study. See also Hoorn's earlier papers.

Howard, J. L., 2000, Provenance of quartzite clasts in Eocene-Oligocene Sespe Formation: paleogeographic implications for Southern California and the ancestral Colorado River: Geological Society of America Bulletin, v.112, p.1625-1649.

> Thin section studies of quartz clasts from the Sespe Formation in the Santa Monica Mountains suggest that the Colorado River may be as old as Paleocene.

Huber, N.K., 1990, The Late Cenozoic evolution of the Tulumne River, central Sierra Nevada, California: Geological Society of America Bulletin, v. 102, p. 102–115.

Erosional remnants of volcanic rocks deposited in the ancestral valley of the Tuolumne River permit the partial reconstruction of its course and show that as much as 1525 to 1530 m of local erosion has taken place in the last 10 Ma. Implications for uplift of Sierra Nevada Mountains discussed.

Hunt, C.B., 1969, Geologic history of the Colorado River: U.S. Geological Survey Professional Paper 484, 85 p.

Hunt cites many examples of channels in the Colorado Plateau crossing active domes.

Johnson, W.D., 1905, The Tertiary history of the Tennessee River: Journal of Geology, v. 13, p. 194–231.

Johnson argues for the Tennessee River to be antecedent over Walden Ridge and thus at least Cretaceous in age.

Judson, S., 1976, Evolution of Appalachian topography, in Melhorn, W.H., and Flemal, R.C., eds., Theories of landform development: Proceedings, Sixth Geomorphology Symposium: Publications in Geomorphology, State University of New York at Binghamton, p. 29–44.

Revisits W.M. Davis's (1889) study, "The Rivers and Valleys of Pennsylvania," in which Davis (p. 183) explored the causes of the streams in their present courses: "... to go back, if possible when the several river systems were first implanted." Judson relates drainage reversals of the Appalachians to plate tectonic history and suggests capture rather than superposition. Classic and rich in gems such as "rivers will follow the lowest path across a surface of regional tilt".

Karner, G.D., and Driscoll, N.W., 1999, Tectonic and stratigraphic development of the West African and eastern Brazilian margins: Insights from quantitative basin modeling, in Cameron, N.R., et al., eds., The oil and gas habitats of the South Atlantic: Geological Society [of London] Special Publication 153, p. 11–40.

> Excellent. Combines the offshore record with regional onshore digital terrain maps. For example, the changing volumes of fill in the Santos and Campos Basins (Paleocene to Eocene) are explained by progressive capture by the Paraiba do Sul River, which follows an inland rift system (p. 34–36). Another example is the

Sao Francisco, which captured the Parnaiba during the Eocene (p. 33). Also put forth is the idea that a large river will cut a canyon during a lowstand, but smaller ones (of equivalent discharge) will not. Compare with Cahen (1954).

Kennan, L., 2000, Large-scale geomorphology of the Andes: Interrelationships of tectonics, magmatism and climate, in Summerfield, M.A., ed., Geomorphology and global tectonics: Chichester, John Wiley, p. 167–199.

Most recent overview identifies high-altitude paleosurfaces, and Figure 9.15 diagrams two river systems in Peru and Bolivia that formed these paleosurfaces.

Kolata, D.R., and Nelson, W.J., 1990, Tectonic history of the Illinois Basin, in Leighton, M.W., et al., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 263–286.

Figures 18-5, 18-14, and 18-15 illustrate how closely much of the present lower Mississippi River follows the Early Cambrian Reelfoot Rift.

Lane, L.S., and Dietrich, J.R., 1995, Tertiary structural evolution of the Beaufort Sean-Mackenzie Delta region, Arctic Canada: Bulletin of Canadian Petroleum Geology, v. 43, p. 293-314.

> An outstanding example of how a carefully coupled study of tectonics and sedimentation facilitates inferences about ancient river systems. Here in Northwestern Canada the Tertiary section is post rift and mostly sandstone (shoreward) and shale (seaward) with folding migrating seaward (most intense folding in Eocene and Miocene). Early to Late Tertiary deltas migrated westward and northward in response to eastward and northward propagation of Rocky Mountain deformation (Figs. 2 and 20). Thus the present Mackenzie River System, although totally reorganized in the Pleistocene, has had a long traceable history.

Lay, D., 1940, Fraser River, Tertiary drainage history in relation to placer gold deposits. Part II: British Columbia Mines and Petroleum Resources Bulletin 11, 75 p.

> A detailed report based on a summer's field work outlines the drainage history of the Fraser River, using lavas flows, lake sediments, gravels, drainage patterns, and regional geology. The Fraser River is first identified as pre-Eocene (Late Cretaceous), and is thought to have been flowing to the north rather than westward into the Pacific.

Leopold, E.B., and Lin, G., 1994, A long pollen sequence of Neogene age, Alaska Range: Quaternary International, v. 22/23, p. 103-140.

> Pollen studies help confirm that the Alaska Range was uplifted during the Miocene and thus established at this time much of the present course of the Yukon River across Alaska.

Lucchitta, I., 1989, History of the Grand Canyon and the Colorado River in Arizona, in Jenny, J.D., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 12, p. 701–715.

> Thoughtful paper includes ideas such as "a river is either all old or all young and therefore never had a birth" or "a river is dynamic and therefore always changing and never had a birth and thus different parts may have different ages." Lucchitta believes the Colorado to be at least as old as the Miocene, notes that an important agent of riverine change is tectonism.

Mann, C.J., and Thomas, W.A., 1968, The ancient Mississippi River: Transactions, Gulf Coast Association of Geological Societies, v. 18, p. 187–204.

> "The time of origin of a river drainage system is defined as the earliest date at which a continuing persistent stream occupied a valley" (p. 187). Important article with 12 figures outlines possible ancestral Mississippi drainage from Permian into Pliocene time.

Marshall, L.G., Sempere, T., and Gayet, M., 1993, The Pecta (Late Oligocene-Miocene) and Yecua (Late Miocene) Formations of the sub Andean Chaco Basin, Bolivia and their tectonic significance: Document Laboratoire Géologique Université Lyon, France, v. 125, p. 291–301.

Vertebrate paleontology helps date the "drying up" of a mid-Tertiary shallow sea that once occupied the Chaco of today.

Mathews, W.H., 1992, Physiographic evolution of the Canadian Cordillera, in Gabrielse, H., and Yorath, C.J., eds., Geology of the Cordilleran orogen in Canada: Geological Survey of Canada, Geology of Canada, v.4, p. 405–418 (Decade of North American Geology, v. G-2, Geological Society of America).

> Includes physiographic history since the Jurassic, maps of Miocene-Pliocene basalts and main tectonic events. Key article for western Canada. Model study.

McKee, E.D., Wilson, R.F., Breed, W.J., and Breed, C.S., eds., 1967, Evolution of the Colorado River in Arizona: Flagstaff, Museum of Northern Arizona, 67 p.

> History of the Colorado is divided into five stages, starting with the withdrawal of the Cretaceous Sea (Chapter III). Interesting to follow how complex uplifts and shifting paleoslopes reversed an initially north-dipping paleoslope. Table 1 is remarkable and very detailed and almost one of a kind (but see Grabert, 1967).

McKenna, T.E., 1997, Fluid flow and heat transfer in overpressured sediments of the Rio Grande Embayment, Gulf of Mexico Basin: Transactions, Gulf Coast Association of Geological Societies, v. 7, p. 351–366.

> Figure 1 outlines the Rio Grande Embayment and shows the present Rio Grande to be localized by it, but somewhat off center. Figure 11 is a good downdip cross section of the Tertiary and Cretaceous.

McLean, J.R., 1977, The Cadomin Formation: Stratigraphy, sedimentology and tectonic implications: Bulletin of Canadian Petroleum Geology, v. 25, p. 792–827.

> Schematic mapping of a Cretaceous paleoriver over a wide area shows it to turn north and follow a basin low to the Arctic, as is typical of an underfilled foreland basin (see Weimer, 1992).

McMillan, N.J., 1973, Shelves of Labrador Sea and Baffin Bay, Canada, in McCrossan, R.G., ed., The future petroleum provinces of Canada — Their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 473–517.

> Figure 23 depicts a large Tertiary river system draining central Canada to the Tertiary Basin between Greenland and Labrador. Big thinking far ahead of its time.

Nuttall, C.P., 1990, A review of the Tertiary non-marine molluscan faunas of the Pebasian and other inland basins of north-western South America: Bulletin of the British Museum of Natural History (Geology), v. 45, p. 165–371.

Figure 2 is a continent-wide map of the extent of brackish marine Neogene paleogeography needed to explain the present course of the Amazon.

Parker, G., Paterlini, C.M., and Violante, R.A., 1994, Edad y génesis del Río de La Plata: Revista de la Asociación Geológica Argentina, v. 49, p. 11–18.

Parker et al. argue that about 2.4 Ma the Uruguay captured the Paraná-Paraguay, which formerly had a longer course to the sea via the Saldo Basin.

Pazzaglia, F.J., 1993, Stratigraphy, petrography, and correlation of Late Cenozoic Middle Atlantic coastal plain deposits: Implications for late-stage, passive margin geologic evolution: Geological Society of America Bulletin, v. 105, p. 1617–1634.

Figure 11, based on integrated study of stratigraphy, petrology, and paleontology, is a synthesis of the river evolution of the mid-Atlantic coast since the Late Oligocene. Compare with Poag and Sevon (1989).

Poag, C.W., and Sevon, W.D., 1989, A record of Appalachian denudation in post rift Mesozoic and Cenozoic sedimentary deposits of the U.S. middle Atlantic continental margin: Geomorphology, v.2, p. 119–157.

> A remarkable paper that summarizes in its Table 1 and in the 23 illustrations of its appendix the denudation history of the central Appalachians in the Salisbury Embayment area. Entry points of rivers defined by isopach maps. Subsurface geology is the prime provider of evidence.

Potter, P.E., 1997, The Mesozoic and Tertiary paleodrainage of South America: A natural history: Journal of South American Earth Sciences, v. 10, p. 331–344.

> Overview of continental drainage since the beginning of the Mesozoic includes full reference base. Discusses (p. 332) criteria for the age of a river (but also see Mann and Thomas, 1968) and outlines pre-Miocene extent of Amazon watershed.

Rainbird, R.H., McNicall, V.J., Théreault, R.J., Heaman, L.M., Abbott, L.G., Long, D.G.F., and Thorkelson, D.J., 1997, Pan-continental river system draining Grenville orogen recorded by U-Pb and Sm-Nd geochronology of Neoproterozoic quartzarenites and mudrocks, northwestern Canada: Journal of Geology, v. 105, p. 1–17.

> Stratigraphy and paleocurrent study plus U-Pb and Sm-Nd geochronology are used to identify a vast quartzarenite braided plain system of a Grenville-related foreland basin deposited as long ago as 1.003 Ga. Compare with Archer and Greb (1995) and Pazzaglia (1993).

Robertson, P., and Burke, K., 1989, Evolution of southern Caribbean Plate boundary vicinity of Trinidad and Tobago: American Association of Petroleum Geologists Bulletin, v. 73, p. 490–509.

> Oblique, strike-slip motion of island arc with South American coast diverted Orinoco River behind El Pilar Fault Zone during the last 30 Ma (Fig. 15).

Rod, Emile, 1981, Notes on the shifting course of the Orinoco from Late Cretaceous to Oligocene time: GEOS (Escuela de Geologia y Minas UCV, Caracas), v. 26, p.51-56.

> The Orinoco flowed to the northwest from the Guyana Highlands during the Cretaceous and only later in response to the rising Andes and the Cordillera de la Costa did it turn eastward.

Snavely, P.D., Jr., 1987, Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon-Washington continental margin, in Scholl, D.W., Grantz, A., and Nedder, J.G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins — Beaufort Sea to Baja California: Circum-Pacific Council of Energyand Mineral Resources, Earth Science Series, v. 6, p. 305–336.

> Figure 2 shows a right-lateral fault under both the head of Astoria Canyon and the mouth of the Columbia River. Ancestral Columbia is probably antecedent to uplift of coast range in Middle Miocene.

Sprechmann, P., Aceñolaza, F.G., Gaucher, C., Noqueria, A.C.R., and Pérez, M.I., 2001, Transgresion Paranese: Paleoestuario o brazo del Tethys del Mioceno Medio y/o superior en Sud America: XI Congreso Latinoamericano de Geología y III. Congreso Uruguayo de Geología, Actas No. 206, 1 CD-ROM.

> Figure 2 illustrates the inferred extent of the Mar Paranense, a greatly expanded ancestral Rio de la Plata estuary, which extended almost to Bolivia.

Stallard, R.F., Koehnken, L., and Johnsson, M.J., 1990, Weathering processes and the composition of inorganic material transported through the Orinoco River System, Venezuela and Columbia, in Weibezahn, F.H., et al., eds., El Rio Orinoco como ecosistema: Caracas, Venezuela, Rubel, p. 81–119.

Chiefly a study of the close linkage between landforms, climate, and erosion in the tropics, this paper provides a good overview of the geologic setting of the Orinoco. Particularly useful is Figure 1, a simplified regional map.

Stokes, F.A., Campbell, C.V., Cass, R., and Ucha, N., 1991, Seismic stratigraphic analysis of the Punta del Este Basin; offshore Uruguay, South America: American Association of Petroleum Geologists Bulletin, v. 75, p. 219–240.

Mouth of the paleo-Uruguay River and that of the Paraná localized by a rift (Figs. 5 and 12). A good example of how knowledge of offshore geology is key for dating rivers.

Stott, D.F., Dixon, J., Dietrich, J.R., McNeil, D.H., Russell, L.S., and Sweet, A.R., 1993, Tertiary, in Stott, D.F., and Aitken, J.D., eds., Sedimentary cover of the craton in Canada: Geological Society of America, Decade of North American Geology, v. D-1, p. 439–465.

> A proto-Mackenzie is clearly identified in the subsurface as a depocenter since the Late Cretaceous, and the present MacKenzie has a Pliocene delta (see also Duk-Rodkin et al., 2001).

Szatmari, P., 1983, Amazon rift and Pisco-Jurá Fault; their relation to the separation of North America from Gondwana: Geology, v. 11, p. 300-304.

Plate tectonic constraints call for a megashear underlying much of the main course of the Amazon.

Tempelman-Kluit, D., 1980, Evolution of physiography and drainage of southern Yukon: Canadian Journal of Earth Science, v. 17, p. 1189–1203.

Figures 5a–5c and 7 outline changes in upper Yukon drainage from a Miocene-Pliocene course to the Pacific at the Yukon–British Columbia border, followed by later flow to the northwest, glaciation being responsible for the diversion. See Duk-Rodkine (1994).

Tolan, T.L., Beeson, M.H., and Vogt, B.E., 1984, Exploring the Neogene history of the Columbia River, discussion and geologic field trip guide to the Columbia River Gorge, parts 1 and 2: Oregon Geology, v. 46, p. 87–97, 103–112.

Study of the gorge shows that there was an ancestral Columbia in the Miocene.

Twichell, D.C., Knebel, H.J., and Folger, D.W., 1977, Delaware River; evidence for its former extension to Wilmington Submarine Canyon: Science, v. 195, p. 483–485.

> High-resolution seismic study of Atlantic shelf connects now-far-separated Delaware River from its shelf-edge canyon.

Trettin, H.P., 1991, Middle and Late Tertiary tectonic and physiographic developments, in Trettin, H.P., ed., Geology of the Innuitian orogen and Arctic Platform of Canada and Greenland: Geological Survey of Canada, Geology of Canada, No. 3, p. 493–496; Geological Society of America, The Geology of North America, v. E, p. 493–496.

Develops in more detail the arguments of McMillan (1973) for a Neogene river system in the Arctic Archipelago of Canada.

Violante, R.A., and Parker, G., 1999, Historia evolutiva del Río de la Plata durante el Cenozoico Superior: XIV Congreso Geológico Argentina, Actas 1 Salta, P504-511.

Figure 1 illustrates the Plio-Pleistocene changes of this large estuary.

Weimer, R.J., 1992, Developments in sequence stratigraphy: Foreland and cratonic basins: American Association of Petroleum Geologists Bulletin, v. 76, p. 965–982.

Figures 3 and 16 illustrate paleodrainages of the Midcontinent and foreland basins of the ancestral Rockies. See also Dolson et al. (1991).

Wheeler, H.E., and Cook, E.F., 1954, Structural and stratigraphic significance of the Snake River capture, Idaho-Oregon: Journal of Geology, v. 62, p. 525–536.

Wheeler and Cook conclude that the original Snake River flowed southwesterly from western Idaho, across western Nevada, to Chilcoat Pass. The Feather River diversion was caused by deformation and perhaps volcanic blocking of the former course. They show the importance of volcanism and formation of lakes during course changes of rivers.

Winker, C.D., 1982, Cenozoic shelf margins, northwestern Gulf of Mexico: Transactions, Gulf Coast Association of Geological Societies, v. 32, p. 427–448.

Contains a rare and thought-provoking map of Tertiary drainage basins for the Gulf Coast Basin — a model for all paleodrainage studies? Compare with Dingle and Hendey (1984) and Potter (1994).

Wu, S., and Bally, A.W., 2000, Slope tectonic-comparisions and contrasts of structural styles of salt and shale tectonics of the northern Gulf of Mexico with shale tectonics of offshore Nigeria in Gulf of Guinea, in Mohriak, W., and Talwani, M., eds., Atlantic rifts and continental margins: American Geophysical Union, Geophysical Monographs, v. 115, p. 151-172.

Figure 2 is slightly revised from Winker's (1982) watershed map of the western Gulf of Mexico.

Yrigoyen, M.R., 1993, Morfología y geología de la ciudad de Buenos Aires: Actas Asociasíon Agentina Geologia Applicada Ingeneria, v. 7, p. 7-38.

> Down dip cross section parallel to estuary of Rio de la Plate shows successive step fauling — down-to-sea, down-to-basin — to the southeast reflecting classic passive margin tectonics. See also the stratigraphic section on p. 34. A rare structural analysis under a big metropolis!

Young, R.A., and Spanner, E.E., eds., 2004, Colorado River: Origin and evolution: Grand Canyon Association, Monograph 12, 281 p.

Thirty-three papers include: aerial studies, estimates of rates of incision, geochemistry and uplift, processes, and speculations. An unresolved problem is, "Did headward erosion produce one segment or did a closed basin overflow?"

Acknowledgments

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