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Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns

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[1] A new regional compilation of the drainage history in southeastern Tibet suggests that the modern rivers draining the plateau margin were once tributaries to a single, southward flowing system which drained into the South China Sea. Disruption of the paleo-drainage occurred by river capture and reversal prior to or coeval with the initiation of Miocene (?) uplift in eastern Tibet, including ∼2000 m of surface uplift of the lower plateau margin since reversal of the flow direction of the Yangtze River. Despite lateral changes in course due to capture and reversal, the superposition of eastward and southward draining rivers that cross the southeastern plateau margin suggests that uplift has occurred over long wavelengths (>1000 km), mimicking the present low-gradient topographic slope. Thus reorganization of drainage lines by capture and reversal events explains most of the peculiar patterns of the eastern plateau rivers, without having to appeal to large-magnitude tectonic shear. *INDEX TERMS:* 8110 Tectonophysics: Continental tectonics—general (0905); 1824 Hydrology: Geomorphology (1625); 1815 Hydrology: Erosion and sedimentation; 9320 Information Related to Geographic Region: Asia; 1848 Hydrology: Networks; *KEYWORDS:* Tibet, tectonics, geomorphology, erosion, river capture, drainage reorganization. **Citation:** Clark, M. K., L. M. Schoenbohm, L. H. Royden, K. X. Whipple, B. C. Burchfiel, X. Zhang, W. Tang, E. Wang, and L. Chen (2004), Surface uplift, tectonics, and erosion of eastern Tibet from large-scale drainage patterns, *Tectonics*, *23*, TC1006, doi:10.1029/2002TC001402.

1. Introduction

[2] In actively deforming regions, the geometry and evolution of fluvial systems are sensitive to surface uplift. Thus the uplift and tectonic history of these regions may be partially contained in the geometry of the associated river systems, as recorded in the shapes of longitudinal and transverse river profiles and in the geometries of the drainage basins [e.g., *Howard*, 1967; *Seeber and Gornitz*, 1983; *Oberlander*, 1985; *Jackson and Leeder*, 1994; *Cox*, 1994]. Typically, tectonogeomorphic studies of fluvial systems have concentrated on the identification of active geologic structures and the relative rates of uplift across those structures using longitudinal river profiles [e.g., *Hack*, 1973; *Seeber and Gornitz*, 1983; *Merritts and Vincent*, 1989]. However, large-scale drainage basin morphologies can also place important constraints on regional patterns of surface uplift and shear strain, thus providing critical information about the kinematics of crustal deformation [e.g., *Potter*, 1978; *Cox*, 1989; *Summerfield*, 1991; *Ollier and Pain*, 1997; *Brookfield*, 1998; *Hallet and Molnar*, 2001].

[3] One area where analysis of river systems may be particularly useful as a guide to tectonism and surface uplift is in the region of the eastern Tibetan Plateau, where much of the young surface uplift appears to have occurred without the development of significant shortening structures at the surface [e.g., *Burchfiel et al.*, 1995; *Royden et al.*, 1997; *Wang and Burchfiel*, 2000]. Thus study of the river systems that traverse this portion of the plateau remains one of the few avenues for documenting the spatial and temporal pattern of uplift (Figure 1).

[4] In southeastern Tibet, the very low-gradient plateau margin (5 km elevation gain over 1500 km in length), is defined by a regionally continuous, relict low-relief landscape which is now preserved over large aerial extents in the interfluves between deeply incised river gorges. Along the southeastern plateau margin, we interpret this erosion surface to represent a remnant landscape that has not yet equilibrated to present day conditions (i.e., the uplift that has caused the incision of major river canyons) and the spatial continuity of this landscape argues for broad surface uplift and long wavelength tilt of the plateau margin during crustal thickening. Rapid erosion by continental scale rivers (the Salween, Mekong and Yangtze Rivers and tributaries) that run over thousands of kilometers in length, have incised deep bedrock gorges up to 2 to 3 km in depth along the steepest portion of the plateau margin (between the 3500–4500 contour interval; Figure 1). Thus it appears that the older, uplifted

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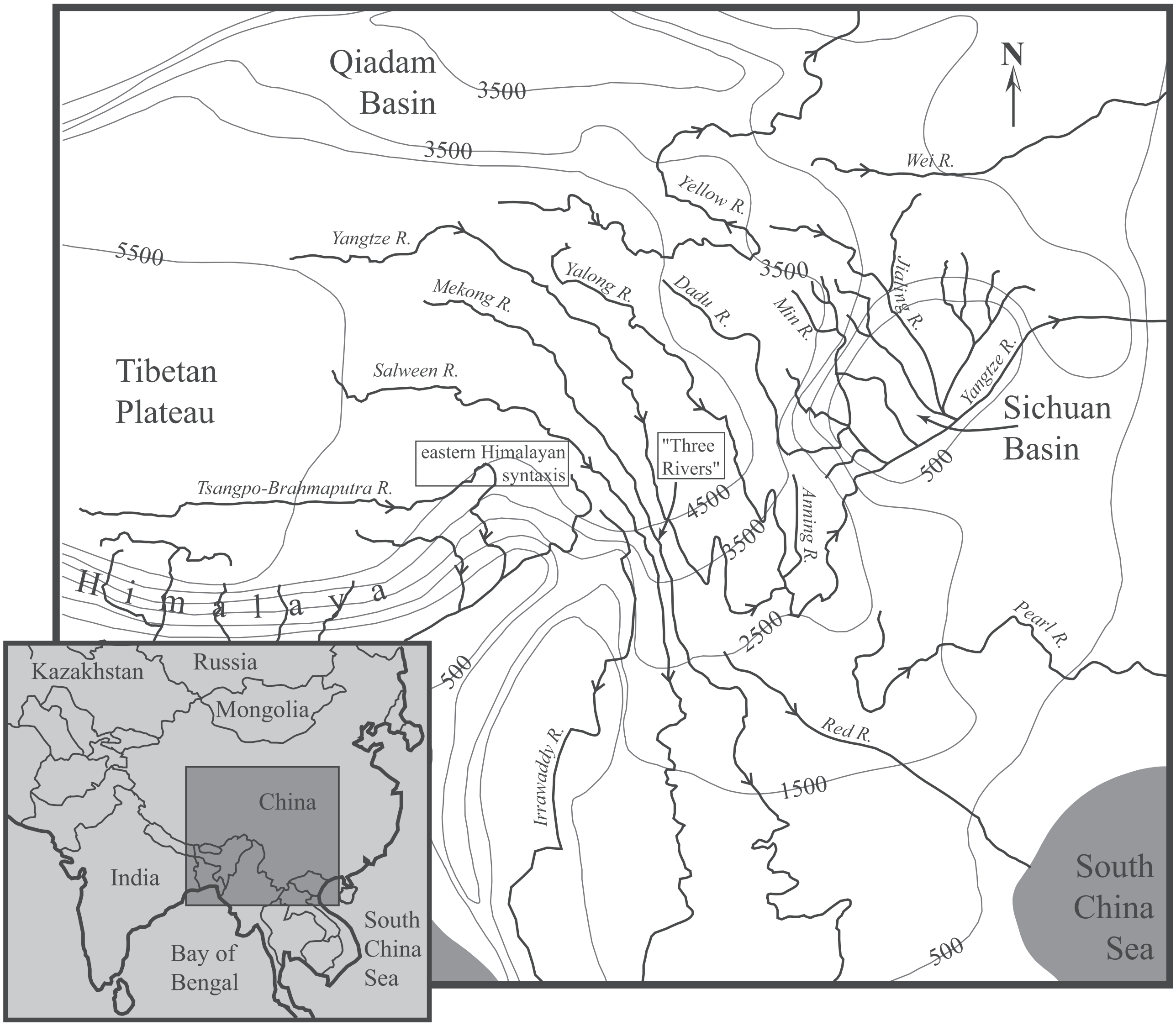

Figure 1. Major river courses of eastern Tibet superimposed on a smoothed elevation contour map derived from publicly available ∼1 km resolution GTOPO30 topography data [*U.S. Geological Survey* (*USGS*), 1993]. Arrows represent modern flow direction. Dark shaded box in inset map shows location of the study area.

low-relief landscape that defines the plateau surface is currently being destroyed by aggressive river incision, presumably in response to the uplift of the eastern plateau.

[5] The major rivers of eastern Tibet have attracted considerable attention due in part to their peculiar drainage basin morphology. Early studies focused primarily on the history and geometry of individual rivers, emphasizing changes in river patterns due to river capture and drainage direction reversal [e.g., *Abendanon*, 1908; *Gregory and Gregory*, 1925; *Lee*, 1933; *Barbour*, 1936]. More recent studies have generally attempted to link the regional fluvial patterns to the rise of the Tibetan plateau and the continental collision between India and Eurasia [e.g., *Koons*, 1995; *Brookfield*, 1998; *Métivier et al.*, 1999; *Hallet and Molnar*, 2001], though some of these recent studies also mention examples of individual river capture events as a partial explanation for one or more of the unusual drainage basin morphologies in southeastern Tibet. An end-member view considers the modern river courses as passive strain markers within the crust, concluding that the unusual drainage pattern in southeastern Tibet has resulted solely from deformation by horizontal shear of initially typical drainage basins during the Indo-Asian collision [*Brookfield*, 1998; *Hallet and Molnar*, 2001]. In this scenario, the central portions of the Salween, Mekong, and Yangtze drainage basins become highly attenuated due to large-scale, right-lateral shear caused by the northward progression of the eastern Himalayan syntaxis.

[6] In this paper we assemble a number of separate geomorphic observations made by various authors, and our own field and digital elevation model (DEM) analyses, in order to assess the importance of river capture, to reconstruct the evolution of the drainage systems, and to examine the implications for uplift of the eastern Tibetan Plateau.

2. Drainage Pattern Analysis and Geomorphology of Southeastern Tibet

[7] Drainage anomalies, defined as deviation from common regional patterns, can provide information on tectonic deformation, and styles of regional drainage patterns can be interpreted as the product of the regional relief on which they form [e.g., *Zernitz*, 1932; *Howard*, 1967]. For example, a "dendritic" pattern describes a river system where branching tributaries enter the trunk stream at wide angles. Where this pattern is observed at a continental scale, this type of drainage pattern reflects erosion of horizontal sediments or beveled, uniformly resistant crystalline rocks and forms in areas of low regional relief. In particular, these drainage basins have predictable length to width ratios [*Potter*, 1978]. While the term "dendritic" may be applied to any such branching system, it is commonly reserved to describe river patterns that occur without pronounced structural or slope control [*Zernitz*, 1932]. In contrast, more narrowly spaced tributary basins with narrow tributary angles are defined as a "parallel" drainage pattern indicating strong (steep) slope control. "Trellis" and "rectangular" patterns have tributary junctions that form at right angles, often with regular spacing, which indicate geometric control by underlying structures or joint systems. Transitional drainage patterns that show a change from one basic type of system to another may reflect changes in exposure of underlying structural geometries, changes in uplift patterns or initiation of surface uplift, and possibly changes in climate by the onset of glaciation.

[8] In Tibet, we attempt to correlate deviations from and changes to basic drainage patterns, with the regional slope and tectonic conditions by which they may have formed. The Longmen Shan plateau margin (adjacent to the Sichuan Basin) and the Himalayan front are similar in morphologic character and are both very steep (~5 km elevation gain over 50–200 km). However, the Longmen Shan differs from the Himalayan front in that it has developed despite evidence for minimal upper crustal shortening of Tertiary age [*Dirks et al.*, 1994; *Burchfiel et al.*, 1995; *Royden et al.*, 1997]. Although modest shortening may be occurring along the Longmen Shan (<3 mm/yr), it is almost an order of magnitude less than the rate of shortening along the Himalayan front [*Lave and Avouac*, 2000; *King et al.*, 1997; *Chen et al.*, 2000]. The drainage systems observed in the Himalaya and the Longmen Shan are typical of transverse or consequent drainage systems developed on steep mountain fronts (Figure 2a): the rivers are short, closely spaced (similar to a "parallel" drainage pattern) with steep river gradients and have incised narrow deep canyons with high local relief [e.g., *Hovius*, 2000; *Kirby et al.*, 2003]. The Brahmaputra and Dadu Rivers are exceptions where the river consists of a short, steep river segment transverse to the mountain range, and a longer, low-gradient river that flows parallel or behind the mountain range, a geometry that is most likely the product of river capture, as described below.

[9] Bedrock river incision is typically modeled as a power-law function of drainage area (as a proxy for discharge) and local channel gradient [e.g., *Howard and Kerby*, 1983; *Howard*, 1994; *Whipple and Tucker*, 1999]. By considering a constant relationship between slope and drainage area throughout a drainage basin, the contribution of drainage area can be "corrected" or excluded so that the channel gradients of different rivers (or segments along a river) can be directly compared and used to reflect spatial variations in uplift rate (i.e., by "channel steepness") [e.g., *Snyder et al.*, 2000; *Kirby and Whipple*, 2001; *Kirby et al.*, 2003]. Analyses of channel steepness for bedrock river channels that cross the Longmen Shan indicate a region of vertical rock uplift localized at the steep plateau margin [*Kirby et al.*, 2003].

[10] The southeastern and parts of the east-northeastern plateau margins have far lower regional topographic gradients than the Himalayan and Longmen Shan plateau margins [e.g., *Clark and Royden*, 2000]. In southeastern Tibet, the active tectonic regime is dominated by strike-slip deformation and associated normal faulting, which accommodate translation of crustal blocks around the eastern Himalayan syntaxis and the contribution of active or Cenozoic upper crustal shortening to the long-wavelength gradient in crustal thickness is also minimal [*Burchfiel et al.*, 1995; *Wang et al.*, 1998; *King et al.*, 1997; *Chen et al.*, 2000; *Wang and Burchfiel*, 2000; *Li and Mooney*, 1998]. Therefore it has been proposed that the bulk of the crustal thickening of these low-gradient plateau margins has taken place by preferential thickening of the lower crust during regional scale flow of lower crustal material [*Royden et al.*, 1997; *Clark and Royden*, 2000; *Shen et al.*, 2001].

[11] The rivers that drain the low-gradient southeast and northeast margins of the plateau have very long axial lengths and therefore much lower average longitudinal gradients than rivers crossing the steep plateau margins (Figure 2b). The scale of these eastern Tibet rivers are comparable to the world's longest and largest river basins but differ in significant ways. Most of the world's largest/longest river basins occur in areas of regionally low-relief, such as cratonic interiors (i.e., Amazon, Mississippi, Congo Rivers). These cratonic rivers have very low longitudinal river gradients (on the order of 10^{-4} or less, based on the averaged gradient of drainage basin relief divided by the trunk river length), are transport-limited (alluvial) rivers, have highly predictable length/drainage area ratios, and have drainage basins that are typically teardrop shaped-typical of regional-scale "dendritic" drainages [e.g., *Zernitz*, 1932]. The major eastern Tibet rivers (the Yellow, Yangtze, Mekong and Salween Rivers) are comparable to other major world river basins in length; however, their drainage basins tend to be attenuated and

irregularly shaped, they are dominantly detachment-limited (bedrock) rivers incised into narrow river gorges over much of their length, and they have average river gradients (10^{-3}) that are at least an order of magnitude higher than average cratonic, alluvial rivers, but still at least 1 to 2 orders of magnitude lower than their steep plateau margin equivalents (i.e., a trans-Himalayan river with an average gradient of $\sim10^{-1}-10^{-2}$).

[12] The other notable characteristic of the major, long rivers that drain the southeastern margin of the Tibetan Plateau is that they are deeply incised into a regionally preserved erosion surface (Figure 2c). The low-gradient southeastern plateau margin is defined by a regionally continuous, relict, low-relief landscape preserved over large aerial extents in between these deeply incised river gorges. While we assume that initial local development of this erosion surface is diachronous, we propose that it existed as a regional surface at low elevations prior to uplift of the eastern plateau margin due to its spatial continuity. Therefore its present day elevation provides an excellent datum for constraining total surface uplift. While the major rivers of southeastern Tibet are deeply incised into narrow bedrock gorges, evidence for ancestral river courses exists in abandoned channels, fragments of abandoned channels (i.e., wind gaps with fluvial sediments) and alluvial capped bedrock terraces that occur up to a kilometer in elevation above the modern channel. Also barbed tributaries along sections of major rivers suggest that portions of these rivers have reversed their flow direction, probably in conjunction with a capture event. These geomorphic observations serve as evidence for a paleo-drainage pattern of southeastern Tibet that predates the most recent episode of rapid bedrock incision and in many places contrasts sharply with the pattern of the present day river courses. Detailed evidence regarding the drainage pattern evolution is outlined in the following section.

3. Reconstruction of Drainage Lines

[13] Commonly cited geomorphic evidence for changes in drainage systems include evidence of river capture,

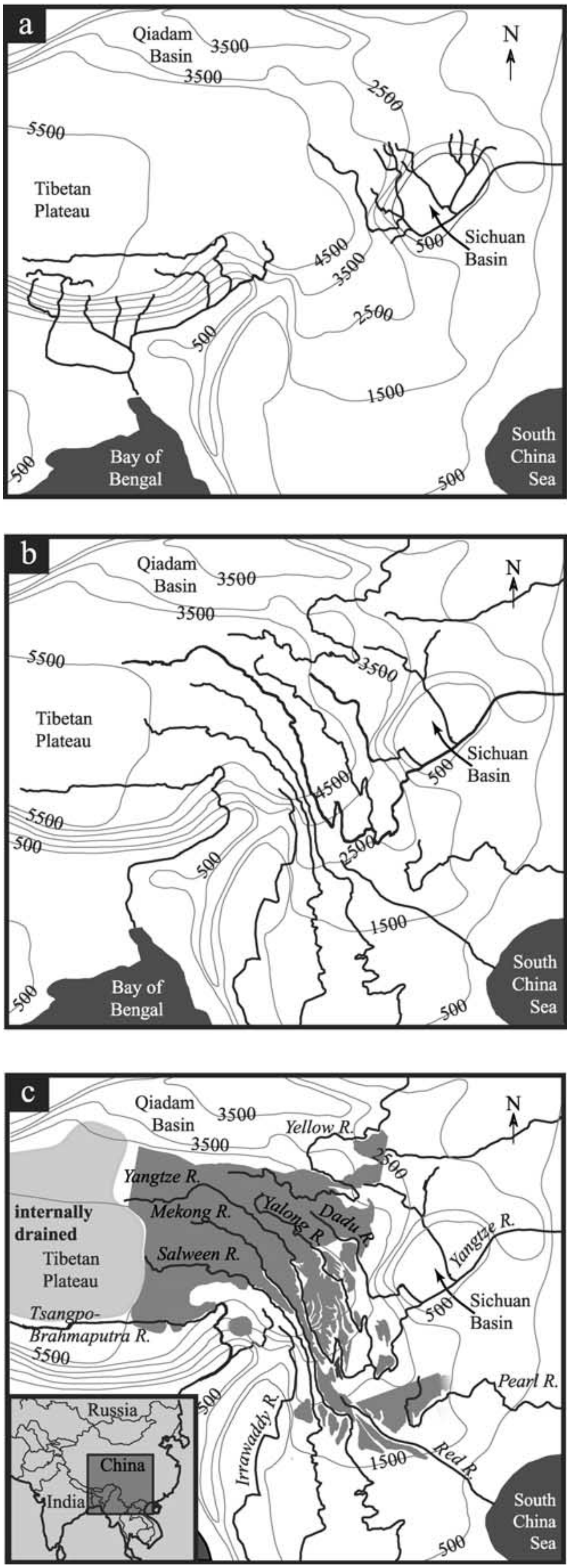

Figure 2. Major rivers of eastern Tibet plotted on topography (smoothed elevation contours in meters). (a) Major rivers that are less that a few hundred kilometers in length and are characterized by steep river profile gradients (corrected for drainage area). (b) Rivers that are more than one thousand kilometers in length and characterized by low-gradient profiles (corrected for drainage area). (c) Generalized extent of regional erosion surface (preserved relict, low-relief landscape), shown in dark-gray shaded regions. Surface is defined from field observations and DEM analyses. At low elevations, this relict surface merges with an ''active'' or modern surface which has not experienced significant surface uplift (represented by gradational shading at the southeastern and northeastern extent of the surface). Light gray shading on high plateau represents the internally drained west central high plateau.

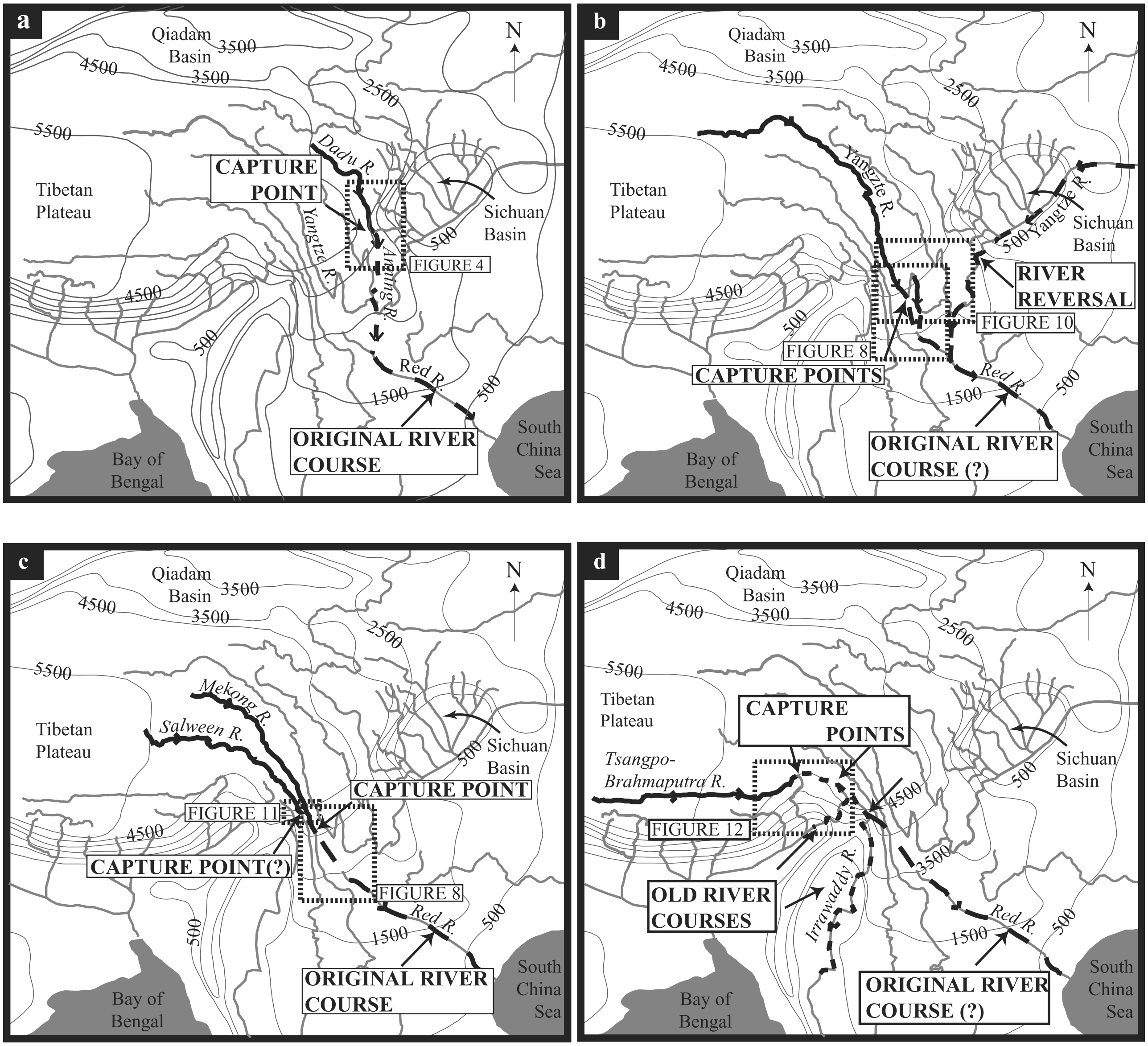

Figure 3. Summary of river captures for eastern Tibet. Small dashed boxes refer to more detailed figures for each capture event. (a) Capture of the Anning River by the Dadu River. (b) Reversal of the Middle of the Yangtze River and capture of the Upper Yangtze River from the paleo-Red River. (c) Capture of the Upper Mekong and possible the Upper Salween Rivers from the paleo-Red River. (d) Successive capture of the Tsangpo River from: possibly the paleo-Red River, the Irrawaddy R., Lhuit R. and most recently by the Brahmaputra River in the area of the eastern Himalayan syntaxis.

remnants of paleo-drainage systems, and drainage reversals. The location of a river capture is commonly indicated by a sharp change in the modern river course with the old river course marked by an abandoned river valley (or ‘‘wind gap’’) that contains fluvial sediments. Occasionally, high fluvial terraces present along the drainage line upstream from the capture point may correlate with the wind gap and define a paleo-longitudinal river gradient prior to capture. Knickpoints (abrupt changes in stream gradient) are also commonly observed on the upstream portion of captured drainage lines. Correlated bedrock terraces, wind gaps, and abandoned river channels (or underfit river channels where the volume rate of flow in the river is smaller than expected for the width of the river valley) can also be used to identify paleo-river courses.

[14] Barbed drainage patterns, where the tributary confluence angles are systematically greater than 90°, are diagnostic of drainage reversal [e.g., *Summerfield*, 1991]. For example, many cited cases of drainage reversal come from the East African Rift, where recent uplift at the rift axis has caused rivers to be defeated (lose their ability to maintain their course and drainage directions) and to reverse

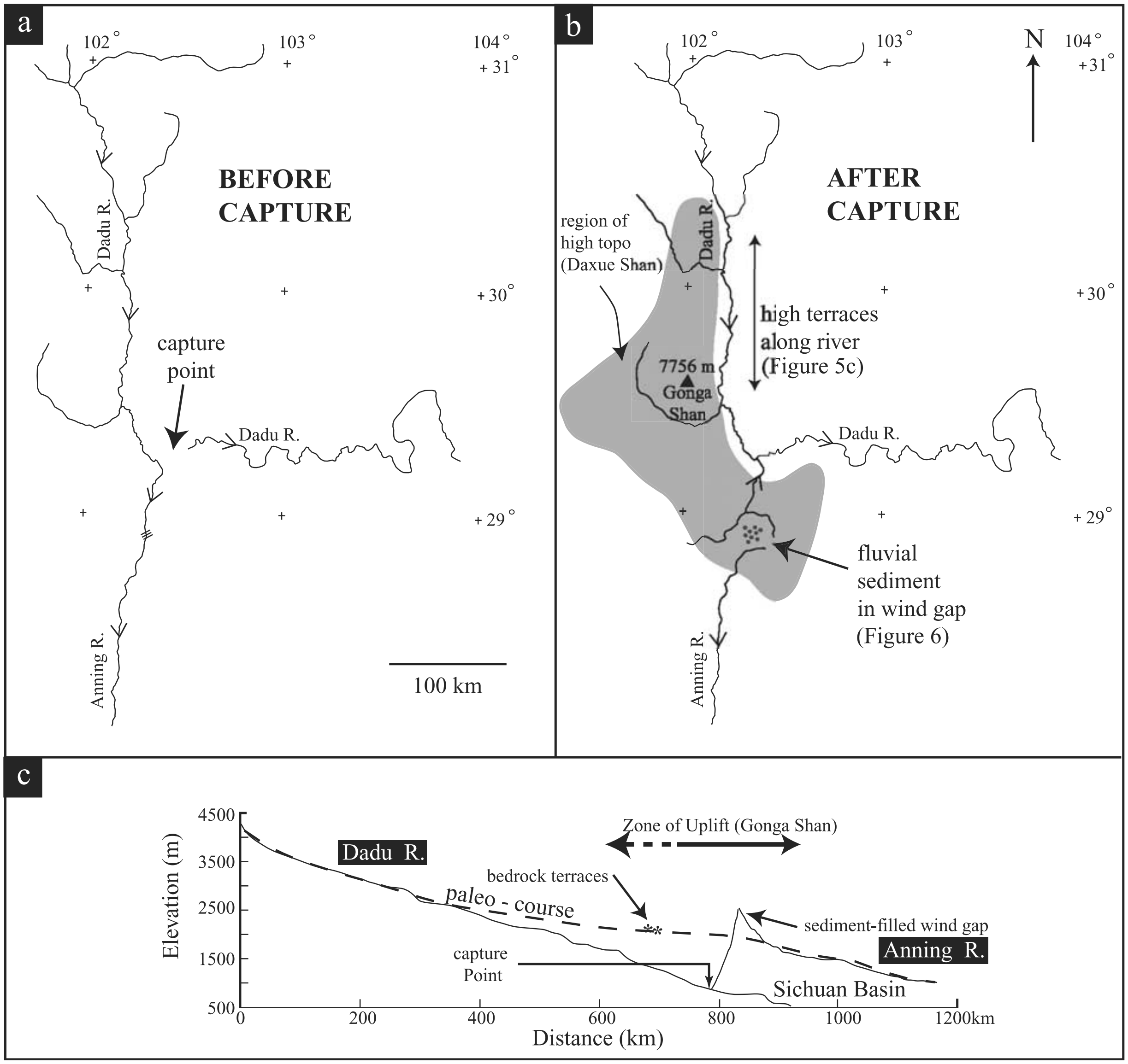

Figure 4. (a) Detailed reconstruction of Dadu-Anning R. capture, where the paleo-Anning River flowed directly south. (b) After capture, the upper reaches of the paleo-Anning are redirected to the east out the Dadu River. Stranded fluvial sediments (shown by stippled pattern) are preserved in the paleo-river course (wind gap), and high bedrock terraces are observed upstream of the capture. Triple line pattern indicates position of restored river course. Capture occurs in the vicinity of anomalously high topography at and around Gonga Shan (7756 m). (c) Longitudinal river profile of the Dadu and Anning rivers, projected onto a north-south profile which is proposed as the reconstructed drainage path. Dashed line represents schematic reconstruction of paleo Dadu-Anning river profile prior to capture.

direction. It has been suggested that such reversal events only occur in areas of minimal relief with very low stream gradients [e.g., *Ollier*, 1981; *Summerfield*, 1991].

[15] Proceeding from east to west, as summarized in Figure 3, we examine the evidence for river capture of major drainage lines in southeastern Tibet, as well as reversal of flow direction along portions of these drainages. The order in which these captures are discussed here is geographical, and in a later section we will suggest a chronology of capture/reversal events with implications for surface uplift of the southeastern plateau margin.

3.1. Dadu/Anning River Capture

[16] The Dadu River is a major tributary to the Yangtze River. It follows a north-south course east of the Longmen Shan range, which forms the steep eastern plateau margin adjacent to the Sichuan Basin (Figure 3a). At its southern

extent within the plateau, the Dadu River is incised into in a narrow deep gorge, makes an abrupt (90°) change in course and flows eastward into the southwestern Sichuan basin (Figure 4). The abrupt change in course occurs adjacent to a low, wide pass (a wind gap) that separates the north-south portion of the Dadu River from the headwaters of the north-south oriented Anning River, also a tributary to the Yangtze River. In contrast to the narrow, deeply incised inner gorges and steep river gradients along the lower Dadu River, the Anning River flows in a broad, alluviated valley with gentle river gradients close to its headwaters, and is presently underfit with respect to its modern drainage area (Figure 5). Fluvial sediments preserved in the wind gap are described as Pliocene(?) (1:200,000 map [*Bureau of Geology and Mineral Resources of Sichuan*, 1991]); however, the age is constrained by neither paleontological nor magnetostratigraphic methods and therefore can only be tentatively assigned. The preserved fluvial gap sediments show a distinct southward dipping slope, despite the modern drainage direction that flows north (Figure 6).

[17] High alluvium-capped bedrock terraces are preserved nearly 800 m above the modern Dadu River just north of the bend and appear to correlate broadly with the wind gap and the low river gradients on the Anning River (Figure 5c). The high terraces, sediment filled wind gap, and low longitudinal river gradients on the Anning River possibly define a paleo-longitudinal profile of the paleo-Dadu/Anning River, indicating that the originally south flowing Dadu/Anning river has been captured by an east flowing river that became the lower Dadu River [*Barbour*, 1936; *Wang et al.*, 1998] (Figure 4c). In the uppermost part of its headwater region, the Anning River abruptly changes to a very steep river gradient leading up to the wind gap where fluvial sediments are preserved at a higher elevation than what would be predicted by simply projecting the upper Dadu River, above the knickpoint related to capture, across the gap (Figure 4c). The oversteepened gradients of the uppermost Anning River and the elevated wind gap lie within a broad region of uplift associated with the adjacent Gonga Shan massif, thus the apparent warping in the reconstructed profile is most likely related to uplift. The elevation difference between the bedrock terraces and the Anning River valley floor beneath the regional erosion surface suggests that 1–2 km of incision occurred prior to the capture event.

3.2. Middle Yangtze River Reversal

[18] For the purposes of discussion, we divide the Yangtze River into three sections: the Upper Yangtze River, defined as the section from the headwaters to the first major bend in the river course (“First Bend”); the Middle Yangtze River

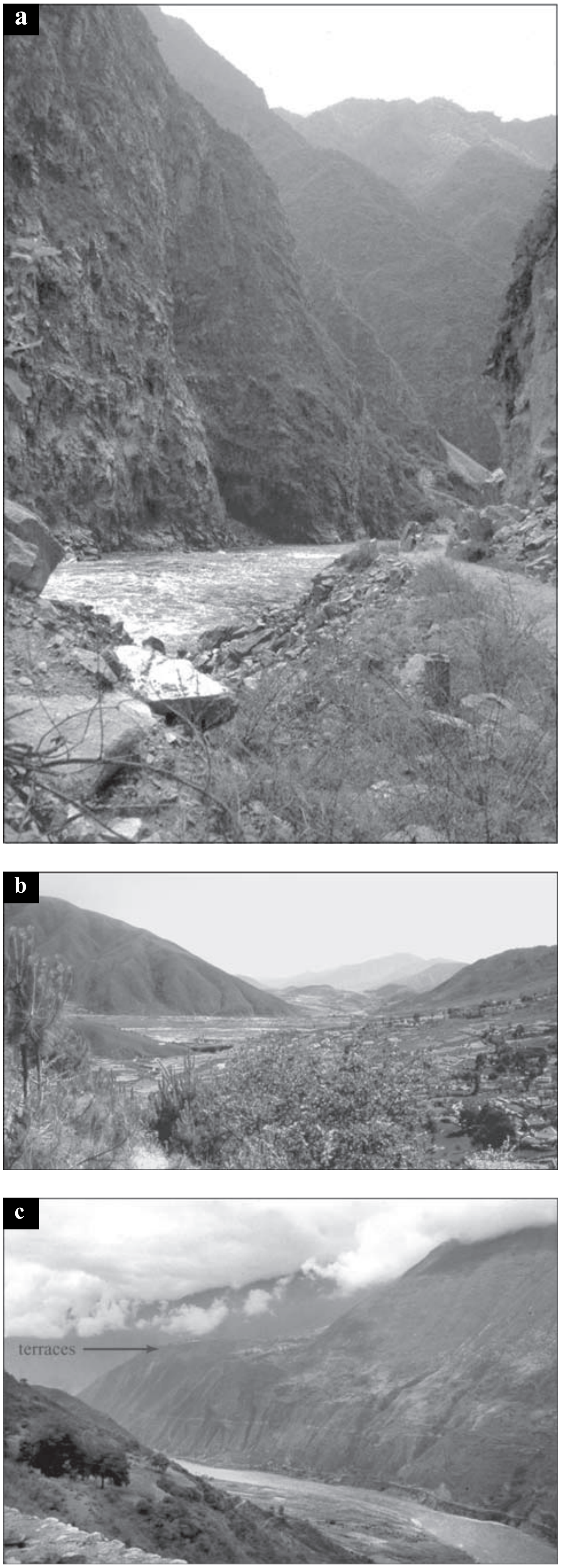

Figure 5. (a) View north of the Dadu River gorge upstream of the capture point. (b) View south of the Anning River valley, from near its headwaters. (c) View southwest at high strath (bedrock) terraces near Luding on the Dadu River. Terraces are approximately 800 m above the modern river elevation.

Figure 6a. View east of wind gap sediments (mid-ground) located in the pass separating the headwaters of the Anning River with the Dadu River. Surface of sediment package dips south.

defined from the "First Bend" to the Three Gorges area, east of the Sichuan Basin; and the Lower Yangtze River defined from the Three Gorges area to the East China Sea (Figure 7a). *Barbour* [1936] first proposed a large-scale reversal of the Middle Yangtze River (including the Min and lower Dadu rivers, but not the Anning, Yalong or Upper Yangtze rivers; Figure 7c), which rerouted the southwest flowing drainage of the Middle Yangtze to a northeasterly course into the Lower Yangtze. This event is supported by the large confluence angles of major tributaries along the Middle Yangtze River (barbed tributaries), reversed terraces, and drainage basin morphology which all suggest that the Middle Yangtze River has reversed its flow direction [*Barbour*, 1936; *Zhao et al.*, 1997]. In this interpretation, the paleo-Yangtze River consisted only of the present Lower Yangtze River, flowing east to the East China Sea (Figure 7a), whereas the modern Middle and Upper Yangtze River are interpreted to have previously flowed south as tributaries to the Red River.

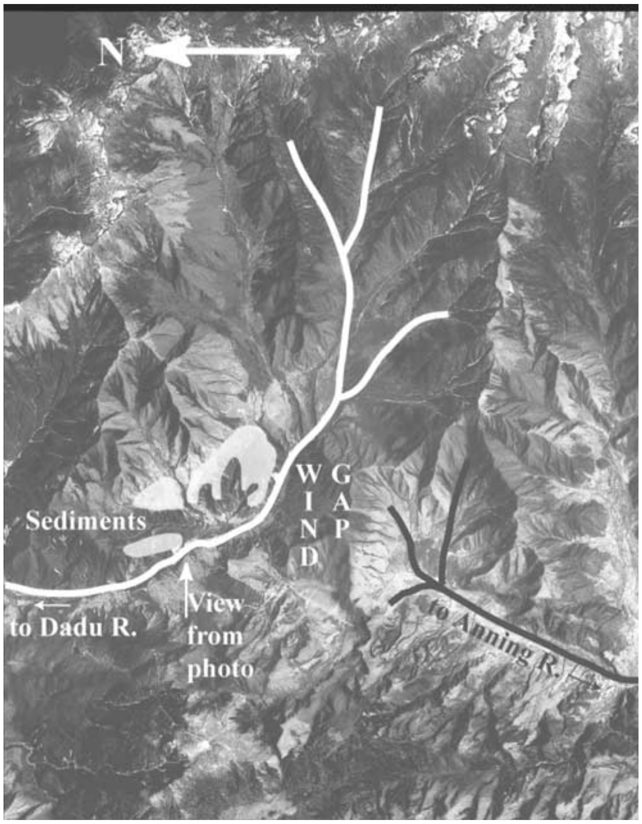

Figure 6b. CORONA image of the wind gap, showing north directed drainage around south sloping gap sediments.

[19] The northeasterly course of the Middle Yangtze River is oblique to the present regional topographic gradient over about 1000 km of its length. Similar to the Upper Yangtze, the Middle Yangtze River is deeply incised into bedrock gorges where the river flows across the southeast plateau margin. It becomes a wider, braided alluvial river when it flows off of the lower plateau margin and along the southeastern margin of the Sichuan Basin. Here the river is moderately incised (a few hundred meters) into the South China Fold Belts with flights of Quaternary alluvial terraces occurring along the river [*Barbour*, 1936]. The river is more deeply incised into bedrock (several hundred meters) where it cuts across basement cored anticlines in the Three Gorges area [e.g., *Abendanon*, 1908; *Gregory*, 1929; *Barbour*, 1936]. By comparison, the Lower Yangtze River is of an entirely different character, flowing on a wide alluvial flood plain for its entire length [*Gregory*, 1929; *Barbour*, 1936].

[20] Because instantaneous large-scale reversal of a river over 1000 km seems unlikely, we propose that the reversal of the Middle Yangtze was accomplished piecemeal by successive reversals of small segments of river and consequent captures of major tributaries into the eastern basin (Figure 7). For example, the initial reversal/capture event was at the Jialing/Yangtze River confluence, where the short segment of Middle Yangtze River upstream from the confluence was reversed, and thus redirected (captured) flow of the Jialing River out to the east into the lower Yangtze River (Figure 7b). In this manner, the reversal of the Middle Yangtze river could have been accomplished by a sequence of river reversals over short segments leading to successive captures of large tributary basins. These captures must have progressed from east to west because reversed channel segments must be diverted away from the basin to the east and into the lower Yangtze River. Thus the eastern portions of the Middle Yangtze must have been diverted first. This proposal extends the original proposal of capture/reversal events by *Barbour* [1936] by including

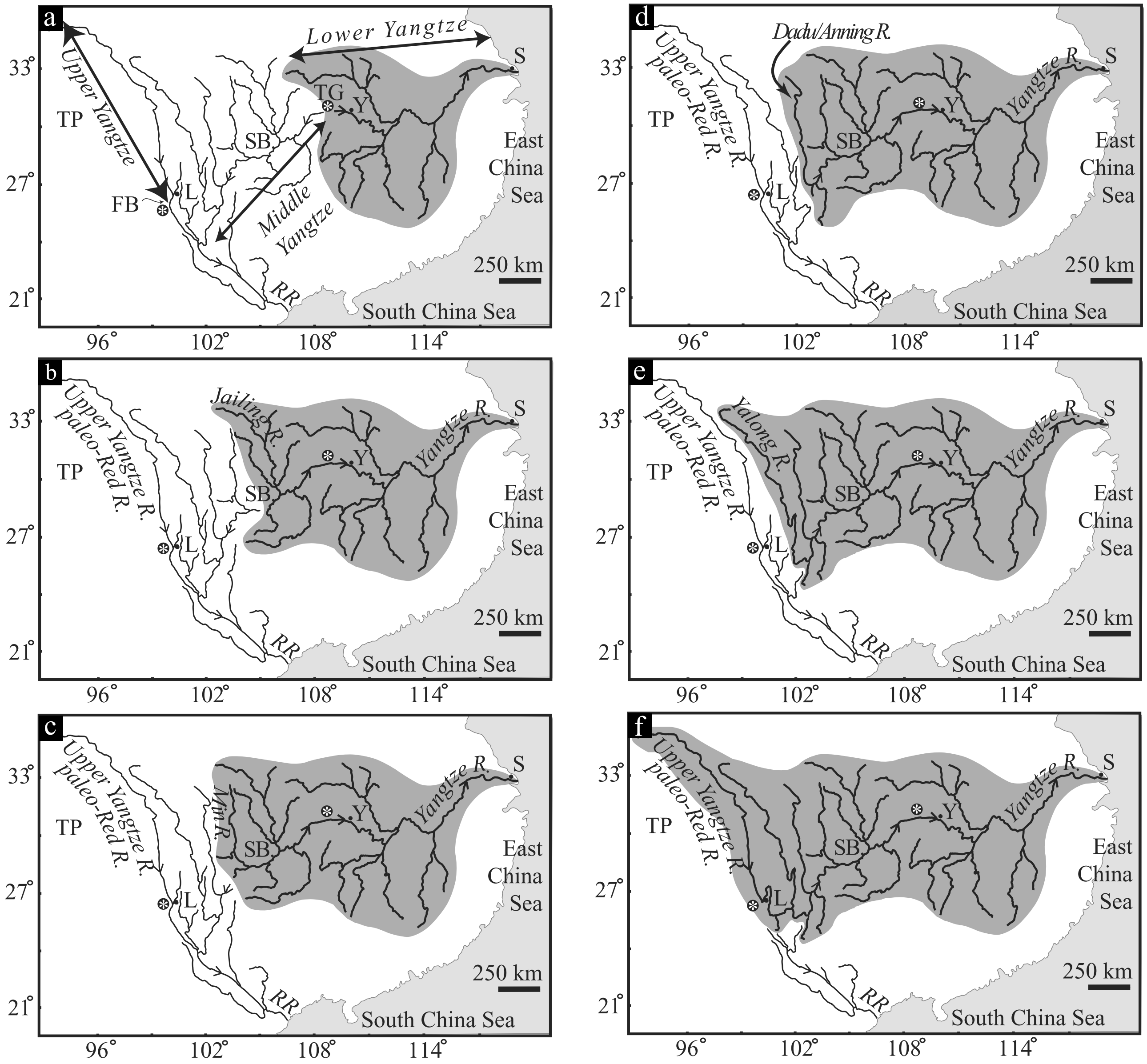

Figure 7. Reversal of Middle Yangtze River and sequential captures of major tributaries to the Middle Yangtze River. Gray outline delineates drainage basin development of the Yangtze River. Asterisk symbols indicate segment of Middle Yangtze that reverses direction, from the "Three Gorges" to the "First Bend". Abbreviations are as follows: FB = First Bend of the Yangtze River, L = Lijiang, RR = Red River, S = Shanghai, SB = Sichuan Basin, TG = Three Gorges, Y = Yichang. (a) Interpreted original drainage basin of the Lower Yangtze River, where the headwaters of this basin are in the Three Gorges region. (b) Reversal of the Middle Yangtze is initiated by the reversal of a small segment of river along the main course and the capture of the Jialing River to the east, into the Lower Yangtze River basin. (c) Reversal progresses from east to west with the capture of the Min River, (d) the Dadu/Anning River, (e) Yalong River, and (f) terminates with the capture of the Upper Yangtze River at the "First Bend," which results in the modern drainage basin morphology.

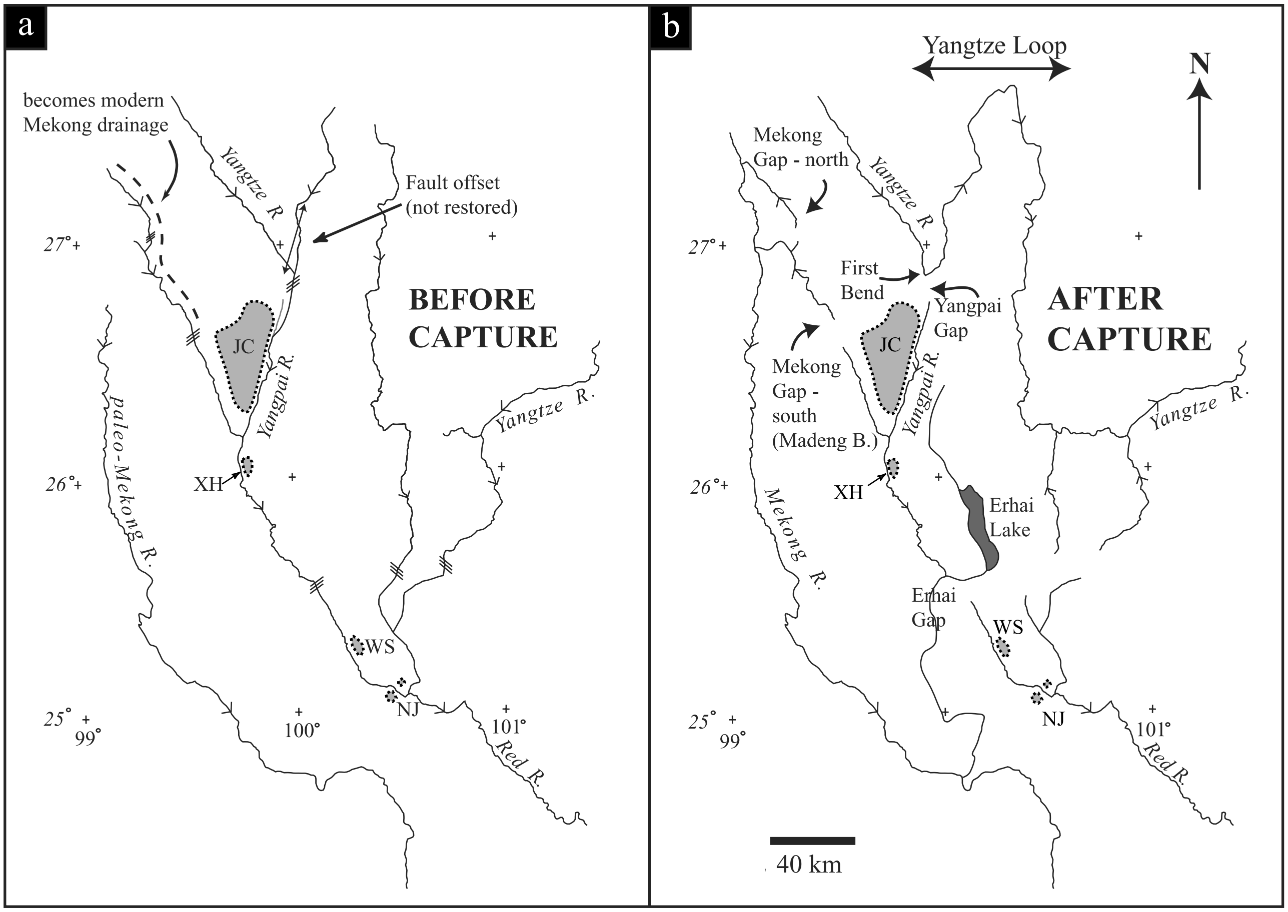

Figure 8. Detailed reconstruction of the Upper Yangtze and Upper Mekong river captures. (a) Prior to capture, the Upper Mekong River and the Upper Yangtze River flowed into the paleo-Red River. (b) After capture, the Upper Mekong is redirected into the (modern) Mekong River, and the Upper Yangtze is redirected to the east, through the Middle and Lower Yangtze River as a part of a sequence of river reversals and captures (Figure 7). Triple line pattern indicates location of restored river course prior to capture. Light gray polygons show areas of preserved Tertiary fluvial sediments that may correlate with a paleo-river system prior to capture. Abbreviations are as follows: JC = Jianchuan, NJ = Nanjian, and WS = Weishan, and XH = Xiahou.

the Anning, Yalong and Upper Yangtze Rivers as well (Figure 7).

3.3. Upper Yangtze/Red River Capture

3.3.1. Geomorphology

[21] The Upper Yangtze River flows from the central plateau through the southeastern plateau margin, where it radically alters its south-southeasterly course down the regional topographic gradient to an east/northeast course that trends obliquely across the plateau margin. Geographers as early as the 15*th* century suggested that the Upper Yangtze River and similarly its major tributaries (e.g., the Yalong and Dadu-Anning rivers) originally drained south into either the Mekong River or the Red River [e.g., *Lee*, 1933; *Barbour*, 1936; *Tregar*, 1965; *Brookfield*, 1998; *Métivier et al.*, 1999; and references therein] (Figure 8). The large amount of Cenozoic offshore sediment in the Gulf of Tonkin is difficult to explain by the modern drainage area and sediment supply of the Red River, suggesting that the drainage area of the modern Red River has been reduced by capture of its headwaters by the modern Yangtze and Mekong Rivers [*Métivier et al.*, 1999].

[22] It has been proposed that the upper Yangtze was probably a tributary to the Red River and flowed through a wind gap at the southern terminus of the "First Bend" in the river (Yangpai Gap) and another low-lying wind gap (the Erhai Gap) into the modern headwaters of the Red River [e.g., *Gregory and Gregory*, 1925; *Ting*, 1933; *Lee*, 1933] (Figure 8a). However, based on recent fieldwork, we propose that the "Yangpai Gap" (as previously described) is not an abandoned river valley (or "wind gap"), but rather is a narrow structural valley most likely formed by the Jianchuan Fault which has also locally offset the Yangtze River at the First Bend [*Wang et al.*, 1998]. However, east of the Yangpai Gap senso-stricto, we observe a broad, smooth, extremely flat surface that continues across to the north-northwest side of the modern Yangtze River gorge,

where the river is offset ~30 km by the Jianchuan Fault [*Wang et al.*, 1998] (Figure 8b). This local surface however, is at approximately the same elevation as the regional erosion surface which mantles this portion of the plateau margin. From field observations and CORONA imagery, the extremely smooth and flat nature of the surface observed along the reconstructed capture point of the Yangtze, suggests that it may represent the floor of a large alluvial paleo-river (i.e., the paleo-Yangtze-Red River) at approximately the elevation of the erosion surface. On a regional scale, the position of this interpreted valley floor requires only a subtle change in position for the capture of the Upper Yangtze from the Red River from previous reports, yet this change does affect the precise location of potentially recoverable sedimentary deposits that might be used to determine paleo-slope and scale of the river prior to capture (i.e., by methods outlined by *Paola and Mohrig* [1996]). This observation is also consistent with at least the lower portions of the paleo-Upper Yangtze having been a broad alluvial river developed on subdued, low-relief topography at the time of capture, which would allow a reversal/capture to occur.

3.3.2. Sedimentology

[23] The most convincing evidence of river capture comes from relict fluvial sediment preserved in a wind gap directly adjacent to the capture point. While we do not observe sediments in this ideal geometry, we present observations from four localities of preserved fluvial sequences from Jianchuan (40 km south of the proposed wind gap) to the headwater basins of the Red River that we tentatively propose to be remnants of a paleo-south flowing Yangtze/Mekong-Red River system (Figure 8). The Tertiary sedimentary record in the region between the Yangtze "First Bend" and the Red River can be divided into three distinct groups: (1) folded Paleocene-Eocene clastic sediments that are conformable with underlying Jurassic and Cretaceous red bed basins (i.e., the Yangbi, Simao and Chuxiong basins), (2) early-mid(?) Tertiary debris-flow units, and (3) Miocene or Pliocene fine-grained silt, mud, and coal deposits [*Bureau of Geology and Mineral Resources of Yunnan*, 1990]. Thus well-exposed fluvial sequences such as the ones described in the following section exposed along the reconstructed path of a paleo-Upper Yangtze/Mekong-Red River course are unidentified elsewhere in the Tertiary section of this area. However, the lack of index fossils and/or provenance indicators require that the correlation of these individual outcrops are made on their lithologic uniqueness alone.

[24] West of the city of Jianchuan (40 km south of the "First Bend" of the Yangtze River), up to ~800 m of well-exposed middle(?)-Tertiary alluvial/fluvial sandstones are observed (Baoxiangshi and Lijiang formations, [*Bureau of Geology and Mineral Resources of Yunnan*, 1990]), most likely representing a structural depocenter. Interbedded cobble and sandstone beds in the lower part of the section are overlain by massive, well-sorted medium grained sandstones which comprise the middle part of the section (Figure 9a). Sandstone beds frequently contain mud rip-up clasts in the lower 10 cm of the beds and are often separated by thin mud drapes and thicker mud beds that occasionally are bioturbaded and contain fossil leaf hash. Occasionally, we observe irregularly interbedded sandstone and fine-grained siltstone (Figure 9b), and rarely observe preserved of cross-bedding and large-channel scours (~5 m). This sequence is undeformed to slightly tilted and lies unconformably on fossil-bearing Paleocene calcareous mudstone, shale and evaporites [*Bureau of Geology and Mineral Resources of Yunnan*, 1990]. We did not observe the top of the Baoxiangshi and Lijang formations; however, Chinese maps indicate that the section is capped unconformably to the north of Jianchuan by a massive conglomerate sequence, and locally capped south of Jianchuan by a Miocene fossil-bearing, interbedded siltstone and coal sequence [*Bureau of Geology and Mineral Resources of Yunnan*, 1990]. The Baoxiangshi and Lijiang formations and the overlying conglomerate sequence do not contain distinctive index fossils, thus their age can only be constrained from the stratigraphic record to be in between Paleocene and Miocene in age. This sandstone sequence lies within the Jianchuan basin complex, which is a complicated area of sediments that range from Paleocene to the Quaternary and are intruded by a series of sub-volcanic syenites and trachytes, that are in some locations as old as 22–5 Ma [*Shäerer et al.*, 1990, 1994] and in places intrude sediments mapped as Pliocene (1:200,000 map [*Bureau of Geology and Mineral Resources of Yunnan*, 1990]). However, tight age constraints for the Baoxiangshi and Lijang formations are difficult to establish because of the poor exposure of direct crosscutting relationships between these intrusives and the sedimentary sequence in the Jianchuan Basin.

[25] Three additional isolated outcrops of less well-exposed fluvial sandstone sequences similar to the section at Jianchuan can be traced south along the Yangpai River and into the modern Red River drainage (Figure 8). These outcrops are characterized by massive, well-sorted medium to coarse-grained sandstone beds with occasional fine laminations, thin mud-drapes, and occasional fossiliferous mud intervals (Figure 9c). Ripples and rip-up clasts are also common. The uppermost section of the northern-most locality (Xiahou) is capped by fossiliferous strata and gray clays. The sandstone beds at Nanjian (Figure 9c) contain cross-beds and are also irregularly interbedded with fine-grained siltstone. All of these sections rest unconformably on the Mesozoic-early Tertiary Yangbi red bed basin and are mapped as Pliocene, however no distinctive index fossils are present [*Bureau of Geology and Mineral Resources of Yunnan*, 1990]. Unlike the gently warped sandstone units of the Baoxiangshi and Lijang formations, these three outcrops show tectonic tilting, most likely related to either extensional faulting bounding the Diancang Shan (Xiaho) or strike-slip faulting on strands of the Red River Fault (Weishan and Nanjian). Thermochronology in the Diancang Shan suggests that extensional exhumation began 4.7 Ma [*Leloup et al.*, 1993], thus constraining the age of sediments at Xiahou to be at least older than early Pliocene.

3.3.3. Role of Drainage Reversal in Capture Events

[26] The capture of the Upper Yangtze River away from the Red River is not a typical capture event. At the location

of the Yangpai Gap, the river makes an anomalous ~150 km hairpin loop (Figures 8 and 10). From his sketch of the paleo-drainage of northwestern Yunnan *Lee* [1933], proposed that the bend geometry had resulted from a capture event between two originally south flowing tributaries of the Yangtze River. This is supported by large, deeply incised, barbed tributaries of the north flowing segment of the river loop that indicate a paleo-course that flowed to the south (Figure 10). The Yalong River has a similar geometry suggesting that the same coupled capture/reversal event has also determined the Yalong course (Figure 10). This combination of reversal/capture separates the wind-gap and the capture point along the channel. Thus in the case of both the Yangtze and the Yalong rivers, the wind gap is located at the southern terminus of the first bend, while the capture point is about ~100–150 km to the north at the apex of the second bend in the river (Figure 10).

[27] As discussed above, possible reversal/capture events along the east-west flowing section of the Middle Yangtze would have also diverted the originally south flowing tributaries of the Red River (such as the Yalong and Dadu/Anning rivers) into the east flowing Yangtze [*Lee*, 1933; *Barbour*, 1936] (Figure 7). Determination of the paleo-drainage reconstruction of the secondary captures of the Yalong and Dadu/Anning Rivers are more elusive, because the principle paleo-drainage pattern runs parallel to active graben structures and paleo-river channel sediments can be difficult to distinguish from graben fill in active tectonic basins. Further field studies are needed to reconstruct the drainage pattern in this area in more detail, possibly from drill core and shallow seismic data that would be able to identify paleo-river sediments and sediment architecture in less well exposed areas.

3.4. Upper Mekong/Red River Capture

[28] Just north of the first wind gap separating the Upper Yangtze River from the Red River, is the "Three Rivers" area where the Yangtze, Mekong and Salween are separated by narrow, closely spaced divides (Figure 1). In the "Three Rivers" area, there is a remnant surface preserved between the Mekong and Yangtze rivers with overlying flat-lying Eogene sediments (1:200,000 map [*Bureau of Geology and Mineral Resources of Yunnan*, 1990]). Near the northern extent of this "Three Rivers" area, along the Mekong River, there are two broad, low-gradient barbed tributaries that flow north into the modern south flowing Mekong River (Figure 8). Miocene, Pliocene and Quaternary sediment are preserved in both tributary valleys (1:200,000 map [*Bureau of Geology and Mineral Resources of Yunnan*, 1990; *Wang et al.*, 1998]).

[29] In the southern tributary basin (Madeng Basin), Mesozoic sediments from the Lanping-Simao tectonic unit

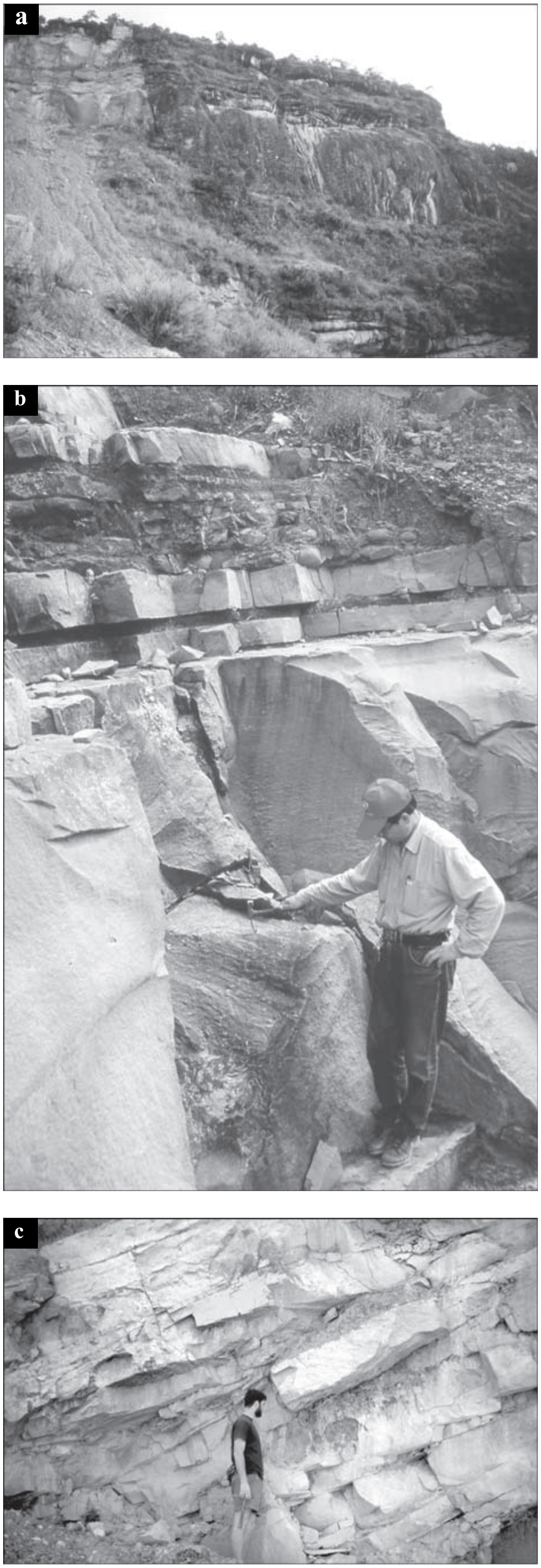

Figure 9. (a) View east of the Baoxiangshi formation near Jianchuan. (b) Close-up photograph of the Baoxiangshi formation, massive sandstones with sections of interbedded mudstones and thin sandstone units. (c) Close-up of thickly bedded sandstone units at Nanjian.

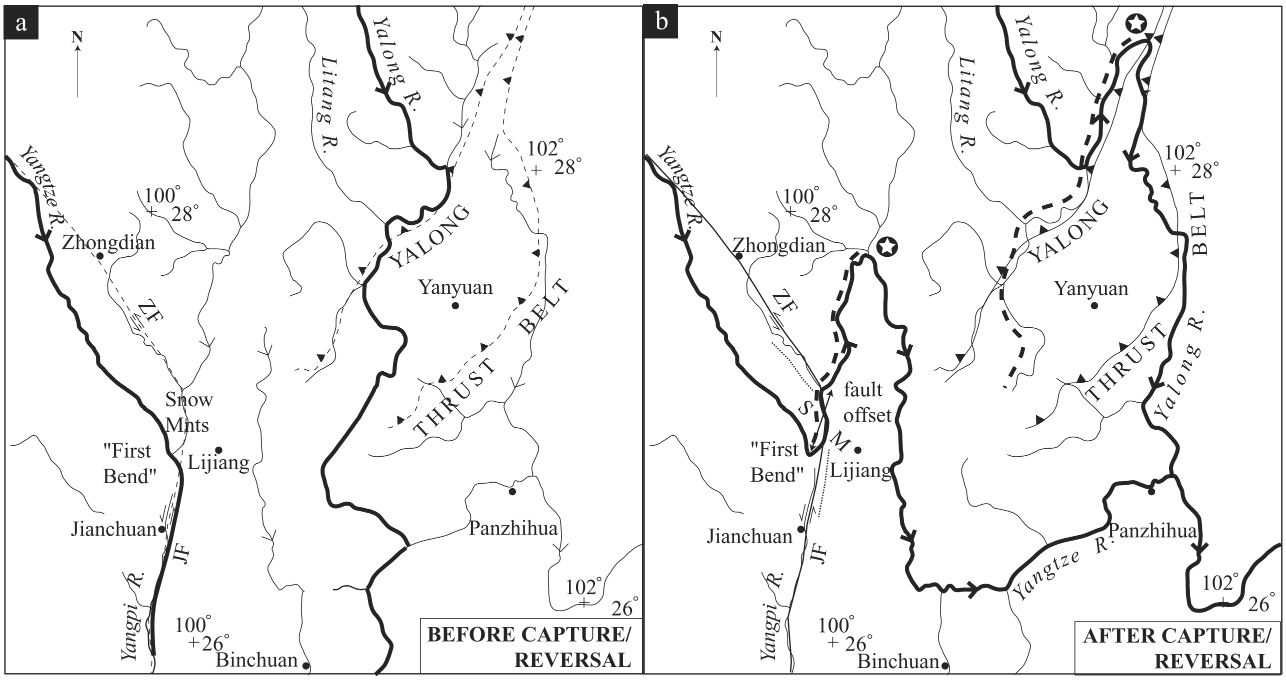

Figure 10. Reconstruction of Yalong and Yangtze River loops. (a) Proposed reconstructed river pattern, prior to reversal and capture. Arrows represent direction of flow along main rivers. (b) Modern river pattern, after proposed capture and reversal events. Heavy line indicates major river course of the main Yangtze and main Yalong Rivers, dashed heavy line indicates segment of river that reverses flow direction and star symbol marks the point of capture. Both Yangtze and Yalong River loops occur along strike of the Yalong Thrust Belt, which is suggested to have a few tens of kilometers of horizontal displacement in Oligo-Miocene time [*Burchfiel et al.*, 1995]. Possibly uplift along the Yalong Thrust Belt, and its southward projection into the Yangtze River, induced backtilting and reversal of tributaries to the Yalong and Yangtze River, resulting in capture of the Upper Yangtze and Yalong rivers to the east. A small segment of the Yangtze loop can be attributed to offset along the Zhongdian/Jianchuan Fault [*Wang et al.*, 1998]. Thinly dotted line represents location of possible pre-capture paleo-channel. Abbreviations are as follows: ZF = Zhongdian Fault and JF = Jianchuan Fault.

extend across nearly the entire basin as isolated hills which suggests that the Neogene and Quaternary sediments in the basin are probably quite thin [*Wang et al.*, 1998] (Figure 8). The Tongdian Fault runs through the Madeng Basin, however the sense of offset and amount of Late Cenozoic activity is disputed [e.g., *Leloup et al.*, 1995; *Wang et al.*, 1998], and the resulting control on the morphology of the basin due to the tectonic activity is uncertain. Compared to the valley where the Jianchuan Fault is located (south of the Yangtze river bend), the Madeng Basin is a much broader, flat floored valley, suggesting either greater fluvial dissection or extensional fault activity.

[30] From recent field work in the southern tributary valley (Madeng Basin), we observed (1) deformed fine-grained, coal-bearing sediments and clays at the north end of the valley, (2) faulted volcaniclastic sediments at the southeastern margin to the basin, and (3) dissected broad Pleistocene alluvial fans. None of these sediments cropping out in the basin could be linked to a through-flowing fluvial system, and therefore did not provide conclusive evidence for a paleo-river course of a south flowing Mekong river through this valley. However, the geographic position, geometry and morphology of the valley is suggestive of a wind-gap geometry between the Upper Mekong River and the Red River (Figure 8).

[31] We propose that the original course of the Mekong River was through the northern and southern wind gaps and then south along the Yangpai River where, in this reconstruction, it would have converged with the reconstructed course of the paleo-Upper Yangtze River before flowing through the Erhai gap to the Red River. Thus we propose that the Mekong River was a major tributary to the Red River system prior to the reorganization of drainage lines in southeastern Tibet. Likewise, the sediment in the catchments of the Upper Mekong River would have contributed to the deposition of the offshore sediment in the Gulf of Tonkin in the South China Sea [*Métivier et al.*, 1999].

3.5. Upper Salween/Red River Capture

[32] Reconstruction of the Salween River is speculative because it has been affected by the young and active deformation and uplift of the region near the eastern Himalayan syntaxis that affects the “Three Rivers” area.

The deformation in this area appears to have disrupted the topography of the area and obscured any potential paleo-river courses. Clearly some strike-slip shear must have occurred in the area where the modern Salween bends to the northwest around the eastern Himalayan syntaxis in the region of the Three Rivers area [e.g., *Hallet and Molnar*, 2001]. However, we suggest that the area of strike-slip shear is confined to the local region where the erosion surface has been strongly disrupted ("Three Rivers" area; Figure 1). We propose that shear in the "Three Rivers" area must be at least limited to the area between the Mekong, Salween, and upper Irrawaddy rivers, because remnants of erosion surface are preserved between the Mekong and Yangtze rivers with flat lying Eogene sediments mantling the surface in this location (1:200,000 map [*Bureau of Geology and Mineral Resources of Yunnan*, 1990]).

[33] We could not distinguish the original course of the Salween River prior to uplift and deformation of the "Three Rivers" area: either the modern course of the Salween represents the original drainage line or the Upper Salween was captured away from the Red River in a manner similar to the Upper Mekong and Upper Yangtze Rivers. If the Upper Salween has been captured, we speculate that capture of the Salween River may have occurred over a relatively low divide at about 28°30′N, where a large tributary to the Salween makes an anomalous loop in the vicinity of a high peak, Mt. Moinigkawagarbo (6740 m) (Figure 11).

3.6. Tsangpo/Brahmaputra Capture

[34] In the vicinity of the eastern Himalayan syntaxis, the east-west flowing Tsangpo River makes an abrupt, tight loop, turning south through an extremely steep gorge into the north-south flowing Brahmaputra River, and eventually draining into the Bay of Bengal. Many authors have proposed that a river capture event is responsible for the unusual drainage pattern and deep incision near this bend in the river course, and assign the Tsangpo's original course through the Parlung River to the Lhuit or Irrawaddy rivers [e.g., *Burrard and Hayden*, 1907; *Seeber and Gornitz*, 1983; *Koons*, 1995; *Brookfield*, 1998; *Zeitler et al.*, 2001]. The geometry of this river suggests that the paleo-Tsangpo River was originally similar in length and gradient to the other major rivers draining the southeastern plateau margin, but that it has recently been captured by one of the short, steep transverse Himalayan rivers (the Brahmaputra River). This drainage pattern/capture geometry is similar to that of the Dadu-Anning capture along the eastern plateau margin where a short, steep transverse river (Dadu River) has captured one of the large tributaries to the Yangtze River (the paleo-Anning River), making an abrupt change in river course at the point of capture.

[35] Major barbed tributaries to the Parlung River indicate a southeastward paleo-flow direction [*Burchfiel et al.*, 2000]. The headwaters of the Parlung are separated from the Lhuit and then the Irrawaddy by low, wide passes in a wind-gap geometry (Figure 12). The proposed capture points of the paleo-Tsangpo-Parlung River lie in the region of the disputed border between India, China and Burma. Because of inaccessibility and limited available topographic data, we cannot evaluate the possibility of preserved of fluvial sediments in these passes. Tentatively, we propose that the paleo-Tsangpo drained through the Parlung River (flowing southeast) into the Irrawaddy River, and that the paleo-Tsangpo-Parlung-Irrawaddy River was first captured by a steep-gradient section of the upper Lhuit River, and most recently was captured by the Brahmaputra. It is possible that the Tsangpo was also a tributary to the Red River system (Figure 3). However, because deformation near the syntaxis must be taken into account, and because the morphology is highly disrupted and inaccessible, it is impossible to identify conclusively the original course for the Tsangpo without careful sediment provenance work in offshore basins.

3.7. Summary of Drainage Line and Drainage Basin Reconstruction

[36] Restoration of the capture events discussed in this paper yield a paleo-regional drainage pattern that resembles a large-scale dendritic network (Figure 13). Such abundant evidence for river capture suggests that some, if not all, of the peculiarity of the modern river drainage basin morphology is due to reorganization of drainage lines instead of shear deformation of the drainage basins by active tectonism as proposed by *Hallet and Molnar* [2001].

[37] Examination of the geometries of the different capture events described here yield three different types of capture. The first type is where a longer, orogen parallel river (behind the range front) is captured by an aggressive, steep transverse river. This type of capture produces an identifiable right-angle bend (or very tight bend) in map view, at the terminus of a steep mountain range. The second type consists of the complicated coupled reversal/capture events that have taken place on the Yangtze River and major Yangtze tributaries. The third type, demonstrated by the Mekong River and possibly the Salween, can be described as a lateral capture, where the drainage direction of the original river course and the capturing river are close to parallel, as opposed to the first example of the transverse river capture, where the two rivers are orthogonal, and the captured river produces a sharp bend in the course of the river.

[38] Figure 14 illustrates what happens to basin morphology when we restore the drainage lines according to the capture events described in the previous section. When all the drainage lines are restored, the original (Lower) Yangtze Basin is a large coastal basin draining to the East China Sea (Figure 7a). The Red River drains most of the continental interior to the south-southeast, while the Mekong, Salween and Irrawaddy are linear coastal basins draining to the south (Figure 14a). After reversal and capture of the Upper Yangtze, and the major tributaries of the Middle Yangtze to the east, the former Lower Yangtze basin is enlarged, extended to the west, and now includes more than half of the original Red River drainage area (Figure 14b). Capture of the Upper Mekong, Upper Salween, and Tsangpo Rivers into the Lower Mekong, Lower Salween and Irrawaddy basins, produces a "bottleneck" basin shape (Figure 14c). The Tsangpo-Brahmaputra drainage looks like it was part of the bottleneck basin, but became decapitated, losing its

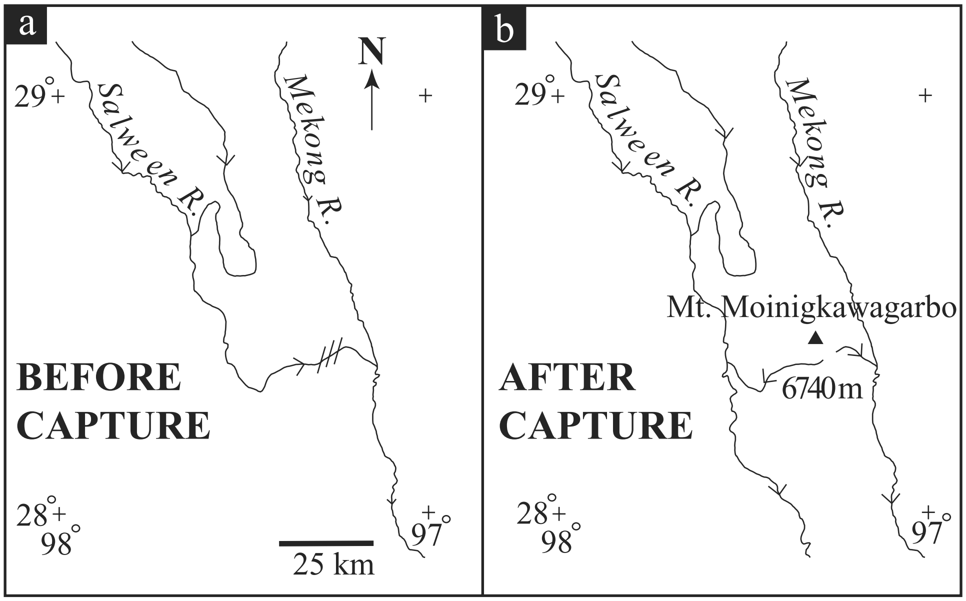

Figure 11. Speculative reconstruction of Salween River capture. (a) Prior to river capture, the Upper Salween may have been a tributary to the Upper Mekong, and thus the paleo-Red River system. (b) We propose that the course of the Salween may have been captured by a steeper river to the south (the modern Lower Salween River) aided by defeat of the original river course into the Mekong by uplift at Mt. Moinigkawagarbo. However, this reconstruction is highly speculative because localized deformation in this area near the eastern Himalayan syntaxis would have obscured any paleo-river courses if they existed.

headwaters to a steeper, more aggressive trans-Himalaya river (Figure 14d).

4. Timing of Drainage Reorganization and Surface Uplift Rates

[39] The timing and geometry of individual capture events and drainage reversals can be used to place constraints on the magnitude and rates of surface uplift. Although the timing constraints for these captures are not well known, in the following section we outline tentative estimates based on published geologic and thermochronometric data.

4.1. Dadu/Anning River Capture

[40] The sediments preserved in the wind gap between the Dadu and Anning rivers are assigned a Pliocene age (1:200,000 map [*Bureau of Geology and Mineral Resources of Sichuan*, 1991]), but these sediments do not have direct paleontologic control. Their age has been tentatively assigned by correlation with similar lithologies of the Xigada Formation that are dated 300 km to the south on the Yangtze River (X. Zhang, personal communication). The Dadu-Anning capture point is associated with an area of anomalously high topography of sub-regional extent (the Daxue Shan and adjacent areas), and the local, uplifted areas of the Gonga Shan massif (Figure 4). Low-temperature thermochronometric ages from this area suggest rapid uplift of Gonga Shan and the Daxue Shan compared to the surrounding region since at least late-Miocene time [*Xu and Kamp*, 2000; *Clark et al.*, 2000, 2001].

[41] The location of the capture point with respect to the region of anomalously high topography and to the proximity of the Sichuan Basin, suggests that the river capture event is likely related to the aggressive headwater retreat of a small transverse river draining the steep Longmen Shan/Sichuan Basin plateau margin and the defeat of the paleo Dadu-Anning river course due to the uplift of the Daxue Shan/Gonga Shan region. Timing of the initiation of uplift of these areas may approximate or provide a lower bound on the timing of river capture. Recent elevation transects of low-temperature thermochronometric data (U-Th/He and apatite/zircon fission track) along the Dadu River suggest a period of slow exhumation that continues from at least 25 Ma to ~8 Ma, followed by rapid exhumation that continues to the present time [*Xu and Kamp*, 2000; *Clark et al.*, 2000]. We interpret the change in exhumation rates to reflect initiation of rapid river incision. Development of the high relief, steep Sichuan Basin margin is interpreted from thermochronometric data that indicate rapid cooling at the basin margin beginning at ~5–12 Ma [*Kirby et al.*, 2002]. High bedrock terraces located along the Dadu River upstream of the capture point (Figure 4c and 5c) are interpreted as remnants of the fluvial channel of the paleo Dadu-Anning prior to capture. These terraces are located approximately 1–2.5 km below the average elevation of nearby plateau surface, indicating significant incision of the paleo Dadu-Anning River prior to capture and an additional

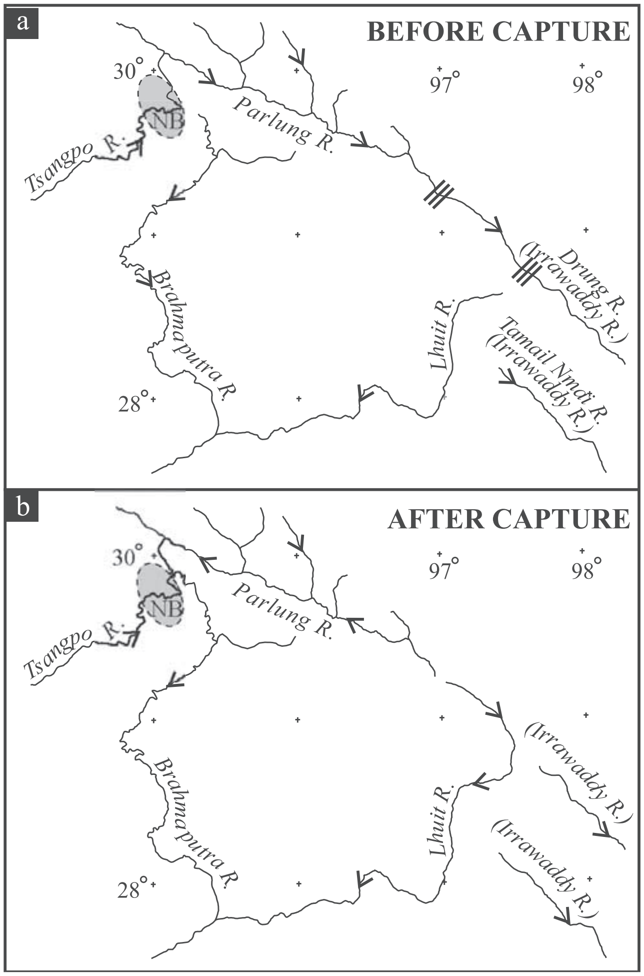

Figure 12. Reconstruction of Tsangpo-Brahmaputra River capture. (a) Prior to capture, the paleo-Tsangpo River flowed into the Irrawaddy River. Shaded area represents the topographic expression of the Nambshebarwa massif (NB) (b) The Tsangpo River was likely first captured by the Lhuit River then subsequently by the Brahmaputra River.

800 m of incision following capture (Figure 4c). We expect that capture may be coeval or postdate the initiation of river incision and the uplift interpreted for the Longmen Shan plateau margin, therefore, we suggest that capture of the Dadu/Anning is probably younger than ~12–5 Ma.

4.2. Brahmaputra/Tsangpo Capture

[42] Wind gaps and capture points associated with the paleo- Tsangpo-Irrawaddy, and the Parlung-Irrawaddy courses occur in an area of both sub-regional anomalously high topography (Nyainqentanglha Shan senso-stricto), as well as localized rapid uplift (Nambshebarwa massif), both of which disrupt a regional low-relief relict landscape (Figures 2c, 12, and 13a). The location of the capture points within the broad high area of the Nyainqentanglha Shan and the proximity of the capture point to the Himalaya topographic front suggest that both aggressive headwater retreat of trans-Himalayan rivers (i.e., the Brahmaputra and the Lhuit rivers) and the uplift of the Nyainqentanglha Shan contributed to river capture (Figure 13a). However, the post-capture river course of the Tsangpo-Brahmaputra rivers crosscuts an area of localized, structural uplift of the Nambshebarwa massif, located just to the south of the sub-regional topographic high of the Nyainqentanglha Shan [e.g., *Zeitler et al.*, 2001]. The crosscutting relationship suggests that the river course is antecedent to the local uplift associated with the Nambshebarwa massif itself (Figure 13a), allowing us to suggest that the capture of the Tsangpo by either the Lhuit River or the Brahmaputra River was prior to ~4 Ma, based on the suggested age of the uplift of the massif [*Burg et al.*, 1998]. River capture prior to the development of the Nambshebarwa massif involving the paleo-Tsangpo would have allowed this river to become sufficiently entrenched in its course so that subsequent uplift would not alter the present river course across the massif.

4.3. Middle Yangtze River Reversal and Capture of Upper Yangtze River

[43] The successive capture events associated with the Middle Yangtze River reversal, terminating in the capture of the Upper Yangtze River, offer an excellent opportunity to correlate the timing of river capture with initiation of major plateau development. It is critical to recognize that reversal of drainage flow direction is thought to occur when a river has a very low longitudinal gradient and is typically not deeply incised into a bedrock gorge [i.e., *Ollier and Pain*, 1997; *Summerfield*, 1991]. In the specific case of the Upper Yangtze and Yangtze tributaries, the wind gaps associated with capture are in broad valleys with elevations not far below the elevation of the regional relict landscape that defines the plateau surface across the southeastern margin. Therefore we infer that the drainage reversals and associated captures along the Yangtze and its tributaries must have occurred when the rivers were flowing in valleys close to the regional low-relief erosion surface, most likely as alluvial rivers, and not in the deeply incised bedrock gorges in which they now flow. Thus the timing of drainage reversal/capture offers the opportunity to establish a lower bound on the timing of the development of significant regional relief and the crustal thickening that is associated with the development of the eastern plateau margin. We can estimate the amount of surface uplift along a section of reversed drainage by using the paleo-course of the river as a horizontal datum. This datum allows us to estimate the total surface uplift since the time of capture.

[44] In the previous section, we discussed our interpretation that drainage flow-direction reversal of a major segment of the Yangtze River consisted of a sequence of river reversals and westward headward erosion over small segments of the river, leading to successive capture tributary basins (Figure 7). In this manner, the timing and initial reversal at the Three Gorges area, the capture of the Jialing River, and the capture of the upper Yangtze River at the "First Bend" bound the time period in which the Middle Yangtze River and its tributaries underwent significant

reorganization. We can estimate the magnitude of surface uplift along the Middle Yangtze River since reversal and subsequent captures by comparing the elevation of the river valley in the Sichuan Basin (average elevation ~500 m), which does not appear to have experienced significant surface uplift in Cenozoic time, with the current elevation of wind-gaps and abandoned channels that formed along the south flowing Middle Yangtze River. The Yangpai gap and all of the other wind gaps that would be related to the southerly course of the Yangtze and its tributaries (Yalong, Dadu/Anning), are currently at ~2500 m elevation. This suggests that ~2000 m of surface uplift in the location of the southeastern plateau margin, along strike of the wind gaps, has occurred since the capture of the Upper Yangtze River.

[45] It will be critical to understand better the timing of the capture of the Upper Yangtze, since it is the last capture that takes place along the reversal of the Middle Yangtze River, therefore offering the tightest constraint on the timing of plateau uplift in this area.

[46] The eastward captures of both the Upper Yangtze and Yalong rivers appear to be associated with portions of the rivers that reversed their flow direction, giving rise to "hairpin" loops in the modern river courses (Figure 10). The northeastern of these two loops, the Yalong loop, is spatially correlated with the Yalong Thrust Belt, which has been interpreted as the southward continuation of the Longmen Shan Thrust Belt [*Burchfiel et al.*, 1995; *Wang et al.*, 1998]. The thrust faults are parallel to the two river "limbs" that make up the Yalong loop, and the thrust belt projects along strike to the Yangtze loop, although it does not outcrop there [*Burchfiel et al.*, 1995; *Wang et al.*, 1998] (Figure 10). We propose that Tertiary activity along these structures may have back-tilted the rivers, inducing or aiding reversal and capture. Assuming that the reversal of a segment of river is associated with the capture, we suggest that the capture event occurred prior to regional uplift of the plateau margin, and also prior to or coeval with the local uplift along the Yalong Thrust Belt. By correlation with the Longmen Shan Thrust Belt, the Yalong Thrust Belt experienced a few tens of kilometers of shortening during Oligo-Miocene time [*Burchfiel et al.*, 1995]. Therefore, an Oligocene to mid-Miocene estimate for the timing of activity on the Yalong Thrust Belt (30–10 Ma), and an estimate of ~2 km of surface uplift along the reversed segment of the Middle Yangtze River, allows us to assign a

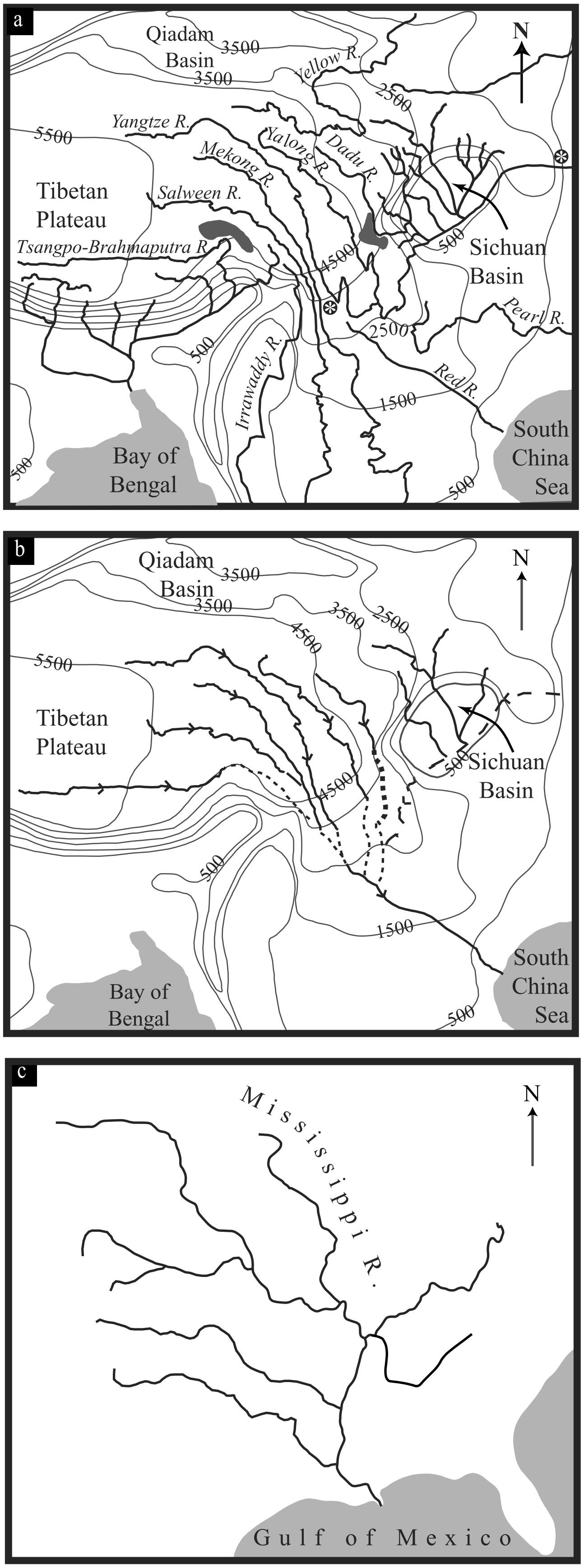

Figure 13. Reconstruction of major river captures in eastern Tibet. (a) Modern major river courses in eastern Tibet. Solid gray areas represent the areas of sub-regional uplift of the Nyainqentanglha Shan and the Daxue Shan. Asterisk symbols mark segment of the Middle Yangtze River that reverses flow direction. (b) Reconstructed river courses (direction and path) prior to major river capture and reversal events. (c) Example of regional scale dendritic patterns of low-relief continental interiors: Mississippi R. of the United States [*USGS*, 1993] at the same scale as the reconstruction in Figure 13b.

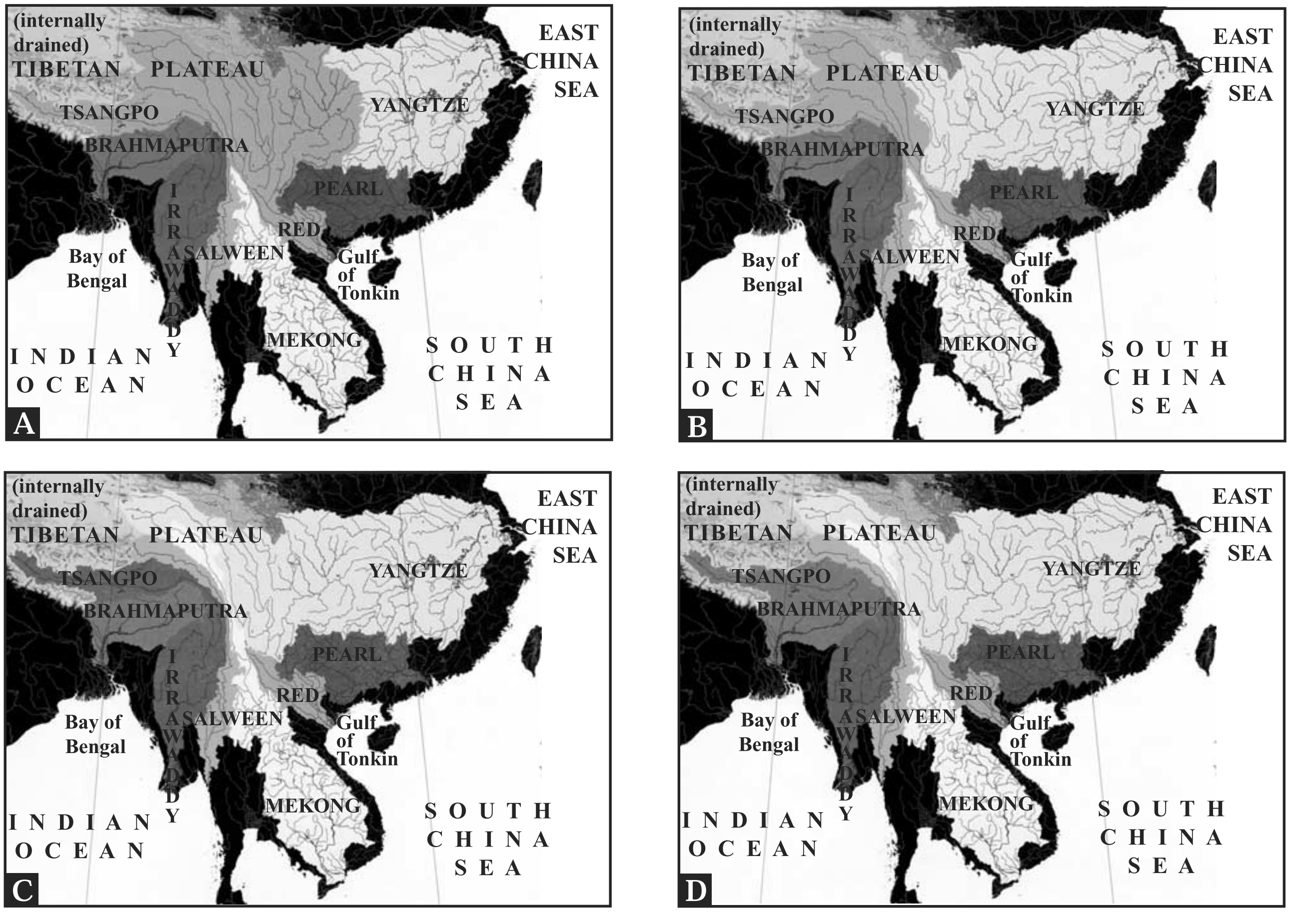

Figure 14. Changes in drainage basin morphology by reconstruction of drainage lines due to river capture/reversals of major rivers in Eastern Tibet. Colors represent individual drainage basins drawn on top of grayscale topography (topography and drainage basin outlines are derived from publicly available HYDRO1K digital topography data [*USGS*, 1993]). (a) Interpreted pattern prior to the major captures, where the Upper Yangtze, Middle Yangtze, Upper Mekong, Upper Salween and the Tsangpo rivers drained together to the South China Sea through the paleo-Red River (blue). (b) Capture/reversal of the middle Yangtze River redirects drainage away from Red River and into the East China Sea through the Lower Yangtze River (green). (c) Capture of the Upper Yangtze River to the east into the Lower Yangtze River, and the Upper Mekong and Upper Salween rivers into their modern drainage positions (green, yellow and orange respectively). Also, capture of the Tsangpo River to the south through the Irrawaddy River (red). (d) Capture of the Tsangpo River through the Brahmaputra River into its modern course (pink). This final configuration is the modern drainage basin pattern. See color version of this figure at back of this issue.

very speculative range of averaged surface uplift rates of ~0.1 mm/yr (0.07–0.2 mm/yr).

5. Tectonic Implications of Reconstructed Drainage Patterns

[47] Capture events affecting major rivers of southeastern Tibet have been proposed in disparate works by many authors for nearly a century [e.g., *Abendanon*, 1908; *Burrard and Hayden*, 1907; *Gregory and Gregory*, 1925; *Lee*, 1933; *Barbour*, 1936; *Tregar*, 1965; *Koons*, 1995; *Brookfield*, 1998; *Métivier et al.*, 1999]. Compilation of these observations in a regional tectonic context, combined with new field work and DEM analyses, yields a salient first order pattern to the drainage history of the southeastern Tibetan Plateau. We suggest that the modern drainage pattern can most easily be understood with the restoration of individual capture events as proposed for the major rivers of southeastern Tibet. Thus reorganization of drainage lines by capture and reversal events can explain most of the peculiar shapes of the drainage basins of these rivers, without having to appeal to large-magnitude tectonic shear [e.g., *Hallet and Molnar*, 2001].

[48] We stress that this interpretation does not preclude some amount of horizontal shear affecting the shapes of the drainage basins (e.g., dextral shear strain accommodating the relative northward movement of India with respect to Eurasia, especially in the "Three Rivers" area). However, we propose that surface uplift, rather than horizontal shear

strain, has been the primary control on the drainage basin morphology, as uplift has induced changes in drainage lines due to river capture and reversal of flow along major river segments. Disruption of the drainage pattern due to local deformation around the eastern Himalayan syntaxis appears mainly limited to the Tsangpo-Irrawaddy and Salween drainage basins where they curve westward around the syntaxis. A smaller amount of distributed shear strain could have modified the shape of the uppermost Salween, Mekong and Yangtze rivers. We do not agree that the drainage lines as they exist today were in place prior to the onset of the Indo-Asian collision (i.e., prior to ~55 Ma) because of the abundant geomorphic evidence of river capture and reversal. We also favor the interpretation that the Tsangpo-Irrawaddy and the Salween were originally major tributaries to the paleo-Red River system and have been subsequently captured by headward erosion of the Irrawaddy and Lower Salween Rivers, not originally individual major drainage basins that have been deformed into their present morphology.

[49] The observations presented here underscore the importance of the reorganization of drainage lines during uplift and erosion of eastern Tibet, and demonstrate how the development of major drainage patterns are related to the uplift history of the plateau margin. The capture events described here for the major rivers in eastern Tibet are related to uplift at local, sub-regional and regional scales-thus offering the possibility of understanding and relating tectonic phenomenon over a broad range of scales.

[50] The Dadu-Anning and the Tsangpo-Brahmaputra River captures have similar geometries and appear to be related to sub-regional uplift of the plateau adjacent to steep plateau margins. Both involve the capture of a relatively long, large drainage line of moderate to low gradient by a short, steep transverse river that drains a steep plateau margin. Both captures are spatially correlated with sub-regional areas of extreme relief and anomalously high topography that also disrupt the erosion surface which defines the eastern plateau, and are associated with very young low-temperature thermochronometric ages. We observe a spatial correlation of these areas of high relief and high topography with concave-indentations (in plan view) of steep plateau margins (Figure 13a). These indentations develop in areas where we interpret weak lower crustal material from beneath the plateau to be flowing around areas in the foreland where lower crustal flow is essentially absent. Geodynamic modeling suggests that these topographic, thermochronometric, and structural observations may be consistent with dynamic topography produced by lower crustal flow [*Clark et al.*, 2001].

[51] In contrast, the reversal of the Middle Yangtze River and capture of its major tributaries to the East China Sea appear to have resulted from the large-scale initiation of plateau uplift along the entire southeastern Tibetan plateau margin. The proposed piecewise reversal of the Middle Yangtze is not associated with any single structure nor set of related structures along the Middle Yangtze. Broad scale tectonic uplift or tilting of the plateau margin would likely be a candidate for the cause of such a regional scale reversal. However, the more local scale reversed segments of river at the capture points of the Yalong and Yangtze bends may be related to activity on local structures.

[52] The reconstruction of drainage lines in this paper suggests that the paleo-drainage network of southeastern Tibet resembles the large-scale dendritic patterns observed in continental interiors commonly developed in areas of low regional relief (i.e., the Mississippi, the Amazon, the Zaire (Congo) Rivers) (Figures 13c and 14). We propose that the initial drainage patterns of eastern Tibet were formed on a regional low-relief landscape (i.e., low paleo-topographic gradients), on the order of what is observed in continental interior basins. We suggest that the timing of river capture/reversals and the onset of reorganization of regional drainage patterns predate, or are coeval with, initiation of plateau uplift in eastern Tibet.

[53] Understanding the paleo-courses of these rivers and the changes in drainage pattern not only yields information about surface uplift and surface uplift rates, but also about the length scale of surface uplift. Comparison of modern and reconstructed drainage patterns suggest that, with the exception of border between the high, flat plateau and the gently sloping plateau margin, where the Yalong and Yangtze loops have formed, we do not observe evidence for drainage pattern disruption as might be expected by formation of a steep plateau margin propagating through the eastern foreland in time. Therefore, we suggest that the uplift of eastern Tibet most likely occurred over long wavelengths.

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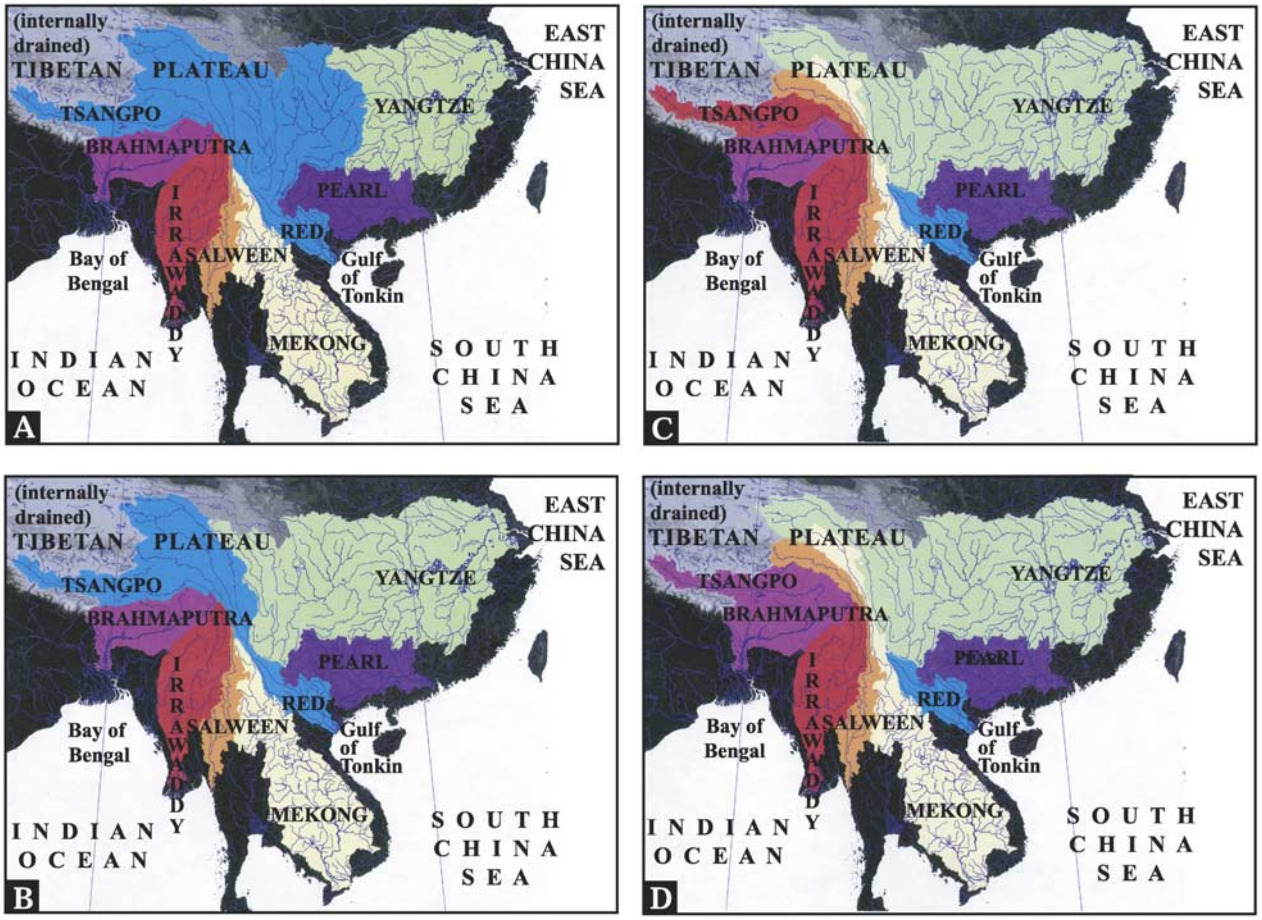

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