Upper Oligocene–Lower Miocene Gangrinboche Conglomerate in the Xigaze Area, Southern Tibet: Implications for Himalayan Uplift and Paleo-Yarlung-Zangbo Initiation

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ABSTRACT

The Gangrinboche Conglomerate, exposed along the Yarlung-Zangbo suture zone, records a crucial stage of the Himalayan orogeny. The type section of these strata in the Xigaze area, southern Tibet, including the Qiuwu and Dazhuka Formations, was studied by integrated stratigraphic, sedimentologic, petrographic, and geochemical techniques. Palynological data and detrital zircon U-Pb ages indicate that the Qiuwu Formation was deposited during the latest Oligocene to the earliest Miocene (most probably ~23 Ma), while the overlying Dazhuka Formation was deposited during 23–18 Ma. The Qiuwu Formation was deposited in a deltaic setting, and detritus was entirely derived from the Gangdese magmatic arc in the north. The Dazhuka Formation, in contrast, was deposited in mainly braided river environments and contains clasts derived from both the Gangdese arc in the north and the Himalayan orogen in the south. Clasts derived from the south first occur at the base of the Dazhuka Formation and increase in abundance upsection to become predominant at the top of the formation. This indicates active Early Miocene uplift and accelerated erosion of the Himalayan belt. Paleocurrent data from the Dazhuka Formation show westward axial sediment transport, which together with mixed provenance from both sides of the basin indicates that a paleo-Yarlung-Zangbo River running parallel to the suture zone initiated at the very start of the Miocene, although with flow direction opposite to that of the present. Flow reversal and establishment of the modern eastward-flowing course must have occurred later on in the Neogene, possibly initiating rapid uplift and focused erosion of the Namche-Barwa syntaxis. Basin subsidence at the close of the Paleogene and subsequent development of a major longitudinal paleo-Yarlung-Zangbo took place contemporaneously with initiation of the South Tibetan Detachment System and Main Central Thrust farther to the south, probably reflecting onset of the "hard collision" phase of the Himalayan orogeny.

Online enhancements: appendix, tables.

Introduction

The Himalayas, formed by crustal thickening during the protracted collision between the Indian and Asian continents, is the most elevated orogenic belt on Earth (Gansser 1964). The initial timing of the India-Asia collision is indicated by a variety of independent data to be Paleocene to Early Eocene (>50 Ma at least; e.g., Garzanti et al. 1987; Ding et al. 2005; Leech et al. 2005; Zhu et al. 2005; Najman et al. 2010; Yi et al. 2011; Hu et al. 2012), whereas the main mountain building process started about 30 m.yr. later, at the start of the Miocene (e.g., Hodges 2000; Najman 2006; Yin 2006). A crucial turning point in the Himalayan Orogeny occurred during the Late Oligocene–Early Miocene time, marked by the onset of a series of fundamental tectonic, magmatic, and stratigraphic events, such as eruption of ultrapotassic and adakitic magmas in southern Tibet (Chung et al. 2003, 2005), development of major fault systems (i.e., the South Tibetan Detachment System and the Main Central Thrust; Gansser 1964; Yin 2006), as well as rapid

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uplift and accelerated erosion of the mountain belt (Harrison et al. 1992; Najman and Garzanti 2000; White et al. 2002).

South of the Himalayan orogen, the sedimentary record of the Oligocene–Early Miocene turning point has been well documented in the sub-Himalayas, and it is marked by an influx of orogenic materials above a Late Eocene–Oligocene unconformity (DeCelles et al. 1998; Najman and Garzanti 2000; Najman et al. 2001, 2004). By contrast, on the Tibetan side of the orogenic belt, this crucial stage of the Himalayan Orogeny has not yet been well studied. The coeval sedimentary rocks, known as the Gangrinboche Conglomerate, was variously interpreted in tectonic significance (Yin et al. 1999; Aitchison et al. 2000, 2002; DeCelles et al. 2011). Indeed, based partly on interpreting the Gangrinboche Conglomerate, Aitchison et al. (2002, 2007) have proposed that the India-Asian collision did not begin until the Eocene/Oligocene boundary (~34 Ma). Therefore, a detailed study of the Gangrinboche Conglomerate and its implications to regional tectonics is of pressing importance to understand the Himalayan orogenic process as well as the Indian-Asian collision.

In this article, we present an integrated study of the stratigraphy, sedimentology, and provenance of the Gangrinboche Conglomerate exposed in the Xigaze area, southern Tibet. Our objective is to provide a detailed depositional history for the Gangrinboche Conglomerate and to show how our new data document the crucial changes that took place in the geological and geomorphological evolution of the Himalayan mountain belt at this time.

Geological Setting

The Yarlung-Zangbo suture zone marks the contact between the Indian subcontinent and Eurasia (fig. 1*a*). It comprises several different tectonic units that include (1) the Yarlung-Zangbo ophiolites, including discontinuous east-west-trending mafic-ultramafic complexes and radiolarian cherts that were generated in a suprasubduction zone setting between the late Barremian and late Aptian (e.g., Hébert et al. 2003; Ziabrev et al. 2003; Wang et al. 2006); (2) the Xigaze forearc sequences, dominated by Cretaceous (Albian-Santonian) deep-water turbidites and minor carbonates deposited along the southern active Asian margin north of the ophiolitic belt (Einsele et al. 1994; Dürr 1996; Wan et al. 1998; Wang et al. 1999*b*, 2012); and (3) a mélange zone that is exposed immediately south of the Yarlung-Zangbo ophiolites and is characterized by various olistoliths within serpentinite or mud matrix (Liu and Einsele 1996; Sun et al. 2011; Cai et al. 2012).

Two distinct conglomerate belts are preserved along the suture zone (fig. 1*b*). The Liuqu Conglomerate, exposed just south of the Yarlung-Zangbo ophiolites, contains clasts derived from both Indian and Asian continents (Wang et al. 2010). It is therefore considered as a postcollisional unit that records the early erosion of the Himalayan-Tibetan orogen, but its depositional age is still poorly constrained (e.g., Wei et al. 2009; Leary et al. 2012). The Gangrinboche Conglomerate, exposed along the southern margin of the Gangdese magmatic arc, extends from the Kailas area in the west to Namche Barwa in the east over 1500 km. It is considered to record a crucial stage of the Himalayan Orogeny that took place much later than the initial India-Asia collision, but its tectonic significance is still controversial (Yin et al. 1988; Harrison et al. 1992; Wang et al. 1999*b*, 2000; Aitchison et al. 2002; DeCelles et al. 2011).

North of the Yarlung-Zangbo suture zone, the Gangdese arc formed during Late Mesozoic to Paleogene as a result of continuous northward subduction of the Neo-Tethyan slab (Chu et al. 2006; Wen et al. 2008; Ji et al. 2009; Zhu et al. 2011; fig. 1*a*). The magmatic arc consists of granitoid batholiths, unconformably overlain by the Linzizong volcanic successions (Chung et al. 2005; Mo et al. 2008; Lee et al. 2009).

South of the Yarlung-Zangbo suture zone, the Himalayan belt includes four major tectonic domains (Yin 2006; fig. 1*a*): (1) The Tethyan Himalaya, delimited by the Yarlung-Zangbo suture zone in the north and by the South Tibetan Detachment System in the south, consists of Lower Paleozoic to Eocene clastic and carbonate rocks. (2) The Greater Himalaya, delimited at the base by the Main Central Thrust, includes upper amphibolite-facies gneisses and leucogranites. (3) The Lesser Himalaya, delimited at the base by the Main Boundary Thrust, consists of various subunits, including basement and Proterozoic to Eocene sedimentary rocks metamorphosed up to lower amphibolite facies. (4) The sub-Himalaya consists of largely Neogene alluvial sedimentary rocks deposited in the Himalayan foreland basin and subsequently accreted along the Main Frontal Thrust.

Stratigraphy and Sedimentology

The Gangrinboche Conglomerate investigated in this study is exposed just south of the Yarlung-Zangbo River in the Xigaze area (fig. 1*c*; Pan et al. 2004), and consists of the Qiuwu and Dazhuka For-

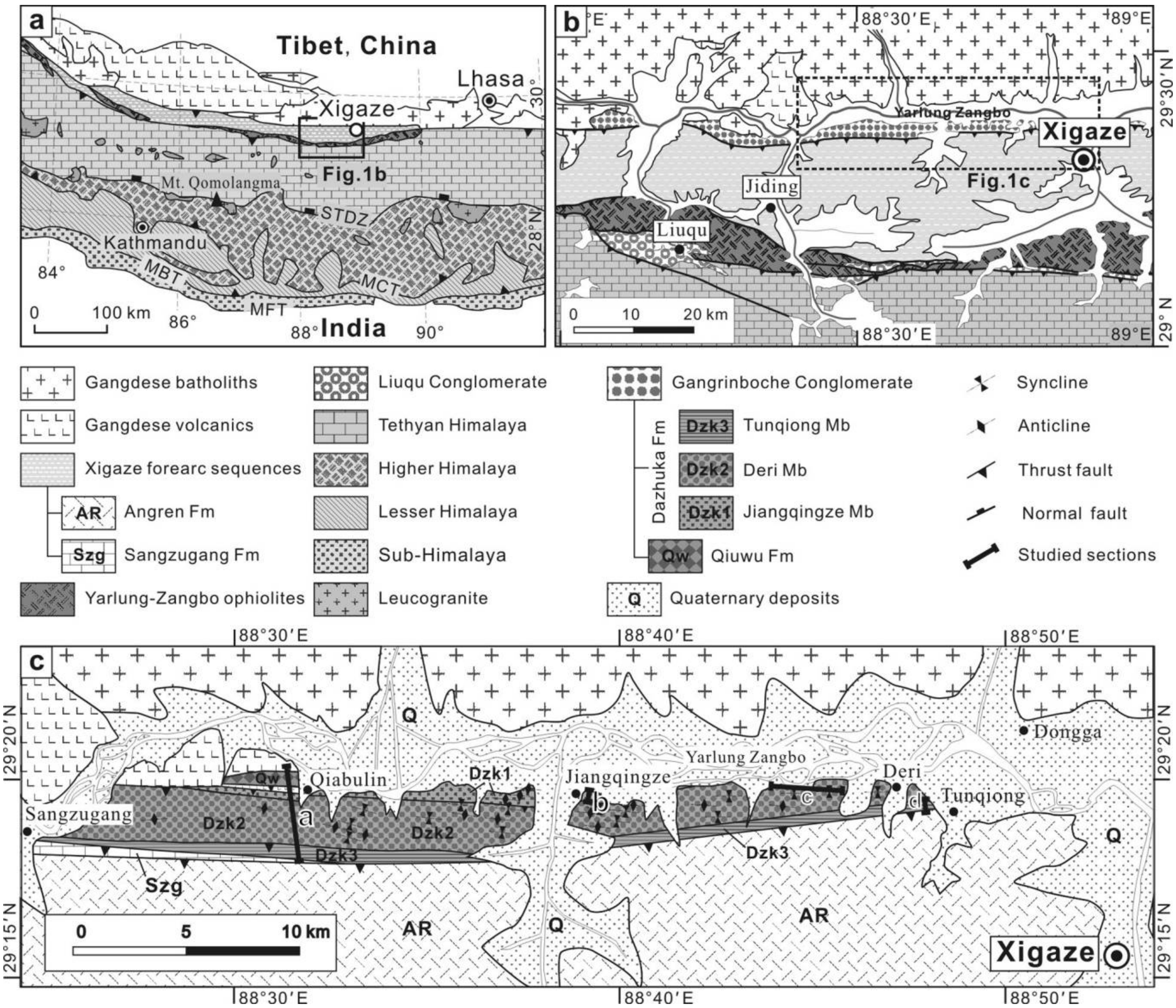

Figure 1. *a*, Simplified tectonic map of the Himalaya and southern Tibet, modified after Yin (2006). STDZ = South Tibet Detachment Zone; MCT = Main Central Thrust; MBT = Main Boundary Thrust; MFT = Main Frontal Thrust. *b*, Geological sketch map of the Xigaze area, southern Tibet, modified after a scale 1 : 1,500,000 geologic map (Pan et al. 2004). *c*, Detailed geological map of the studied area, showing location of measured sections: (*a*) Qiabulin section, (*b*) Jiangqingze section, (*c*) Deri section, and (*d*) Tunqiong section. Mb = Member.

mations (the latter is also named Qiabulin Formation in Chinese literature; e.g., Liu et al. 1996; Wang et al. 1999*b*). We measured these formations in detail in four stratigraphic sections (Qiabulin, Jiangqingze, Deri, and Tunqiong; figs. 1*c*, 2). The observed lithofacies and inferred depositional processes are listed in table 1.

Qiuwu Formation. In the studied region, the Qiuwu Formation occurs only in the Qiabulin section (fig. 2). The strata, deposited unconformably above the Gangdese volcanic rocks (fig. 3*a*), are truncated by a south-dipping thrust at the top. Based on lithofacies associations, the ~400-m-thick Qiuwu Formation can be subdivided into two parts. The lower part consists of ~150 m of massive or thick-bedded gray sandstone interbedded with coal and carbonaceous shale (fig. 3*b*). Trough cross lamination, parallel lamination, and rare tabular cross lamination occur. Fossil plants are abundant. The upper part consists of ~250 m of medium- to thick-bedded sandstones, siltstones, and variegated shales/mudrocks. Sandstone beds may display

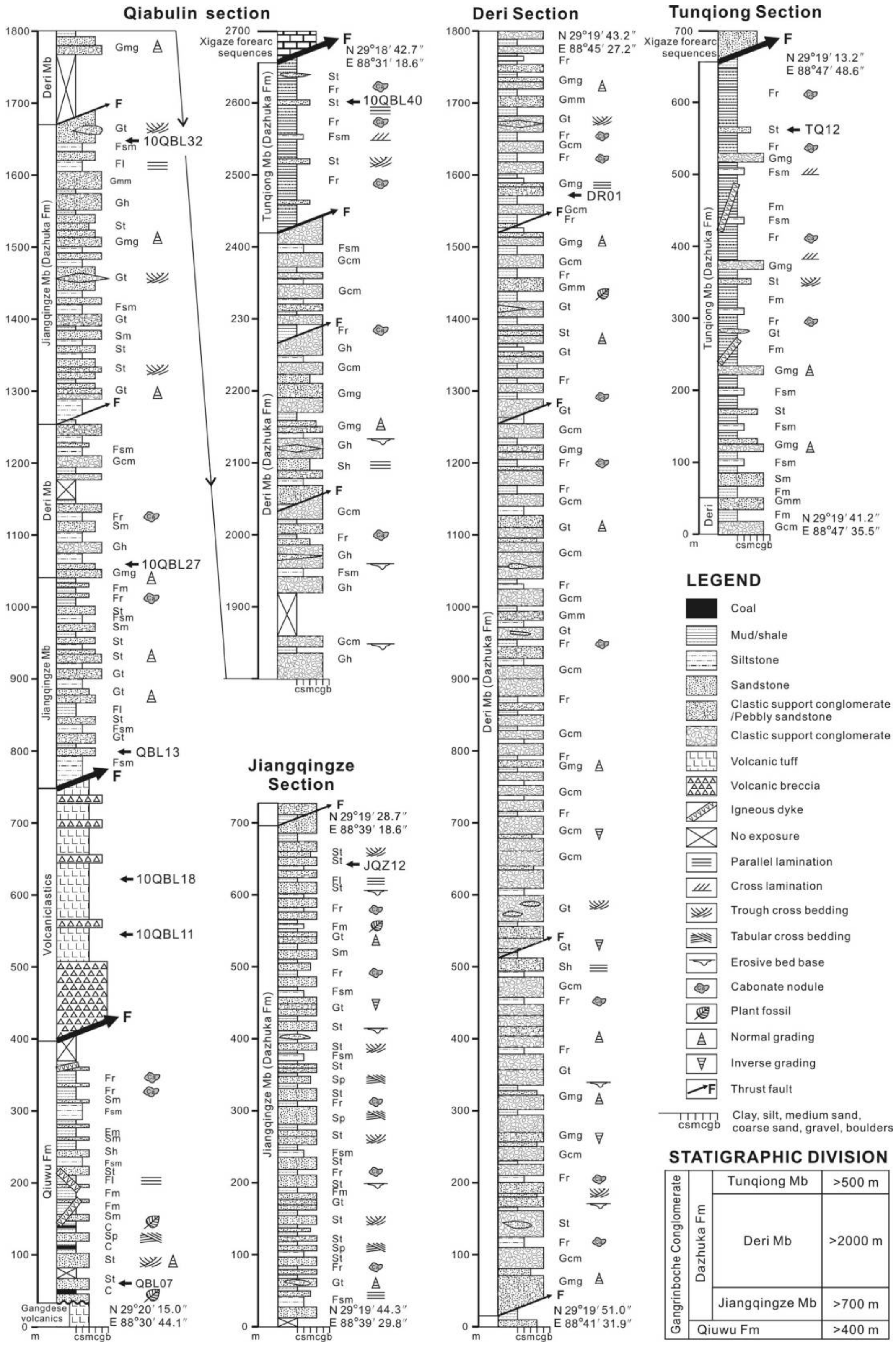

Figure 2. Logs of the Qiabulin, Jiangqingze, Deri, and Tunqiong sections, signed with lithofacies, sedimentary structures, and sample locations for detrital zircon analyses. Stratigraphic division of the Gangrinboche Conglomerate in the Xigaze area is shown on the bottom right. See table 1 for lithofacies codes. Mb = Member.

Table 1. Lithofacies Found in the Gangrinboche Conglomerate in the Xigaze Area, Southern Tibet

Facies code	Description	Interpretation
Gmm	Pebble to cobble conglomerate, angular to round gravel, poorly sorted, matrix supported, massive, disorganized	Cohesive debris flow deposits
Gmg	Pebble to cobble conglomerate, angular to round gravel, moderately sorted, matrix supported, normal grading or inverse grading	Debris flow deposits or braided river channel deposits
Gcm	Pebble to cobble conglomerate, subangular to round gravel, moderately sorted, clastic supported, massive, poorly organized	Braided river channel deposits or clast-rich debris flow deposits
Gh	Pebble to cobble conglomerate, clastic supported, subround to round gravel, moderately sorted, imbricated, poorly stratified	Depostion by traction currents of unsteady flows in alluvial channel or longitudinal bar
Gt	Pebble to cobble conglomerate, subround to well rounded, well sorted, clastic supported, trough cross stratified	Deposition by traction currents in fluvial/alluvial channel
Sm	Massive fine- to coarse-grained sandstone, can be pebbly	Gravity flow deposits in alluvial fan or overbank setting
St	Medium- to very coarse-grained sandstone with through cross stratification	Migration of three-dimensional ripples (dunes) under moderately powerful unidirectional flows in channels
Sp	Medium- to very coarse-grained sandstone with planar cross stratification, can be pebbly	Migration of two-dimensional ripples under moderately powerful unidirectional flows or migration of sandy transverse bars
Sh	Fine- to medium-grained sandstone with parallel lamination	Upper plane bed conditions under strong or very shallow unidirectional flows
Fl	Siltstone or mudstone with horizontal lamination	Distal fan, floodplain, or abandoned channel deposits
Fsm	Massive siltstone	Floodplain or abandoned channel deposits
Fm	Massive mudstone, bioturbated	Floodplain, backswamp, distal fan, or lake deposits
Fr	Immature paleosol with calcareous nodules	Distal fan or floodplain deposits
C	Coal, carbonaceous mud	Plant-rich swamp or distributary bay deposits

Note. Facies codes and environment interpretations are after Miall (1996) and DeCelles et al. (2011).

megaripple and ripple cross lamination or parallel lamination. The color of the mudrock changes upward, from dark gray in the lowest interval to greenish gray in the middle and finally to red at the top, where carbonate nodules are common.

The lower part of the Qiuwu Formation is interpreted as having been deposited in a delta-front environment. The coal and carbonaceous shales represent distributary bay deposits, whereas the cross- or parallel-laminated sandstones represent subaqueous distributary channels or distributary mouth bars. The upper part of the Qiuwu Formation is interpreted as having been deposited in a delta-plain environment. Floodplain or backswamp sediments are represented by lithofacies Fm, Fsm, and Fl, and distributary-channel deposits are represented by lithofacies Sh, Sm, and St (table 1). We proposed that the delta system of the Qiuwu Formation might have developed in a lake, because marine fossils have not been found in it, either by us or by previous workers, and the Tethys seaway has been closed since no later than Late Eocene (Blondeau et al. 1986; Wang et al. 2002; Li and Wan 2003; Hu et al. 2012).

Dazhuka Formation. The Dazhuka Formation is a suite of coarse-grained clastic rocks. A direct contact between the Dazhuka and Qiuwu Formations is nowhere observed in the study area, because Cretaceous volcanic rocks (two samples were dated at 100.6 ± 1.3 and 99.9 ± 0.9 Ma; fig. A1; figs. A1, A2 available in the online edition or from the *Journal of Geology* office) are interposed between them by thrusting. However, their stratigraphic relationships are well documented west of the study area, where the Dazhuka Formation rests conformably on top of the Qiuwu Formation (the Sang'aka section in Anreng County; GPS: 29°23′24.2″N, 87°26′23.4″E). The top of the Dazhuka Formation is invariably truncated by the Great Counter Thrust with the Xigaze forearc strata in the hanging wall (Yin et al. 1994; Wang et al. 1999*b*, 2000; figs. 1*c*, 2). The Dazhuka Formation is subdivided into three members that are characterized by different lithologies, including the Jiangqingze, Deri, and Tun-

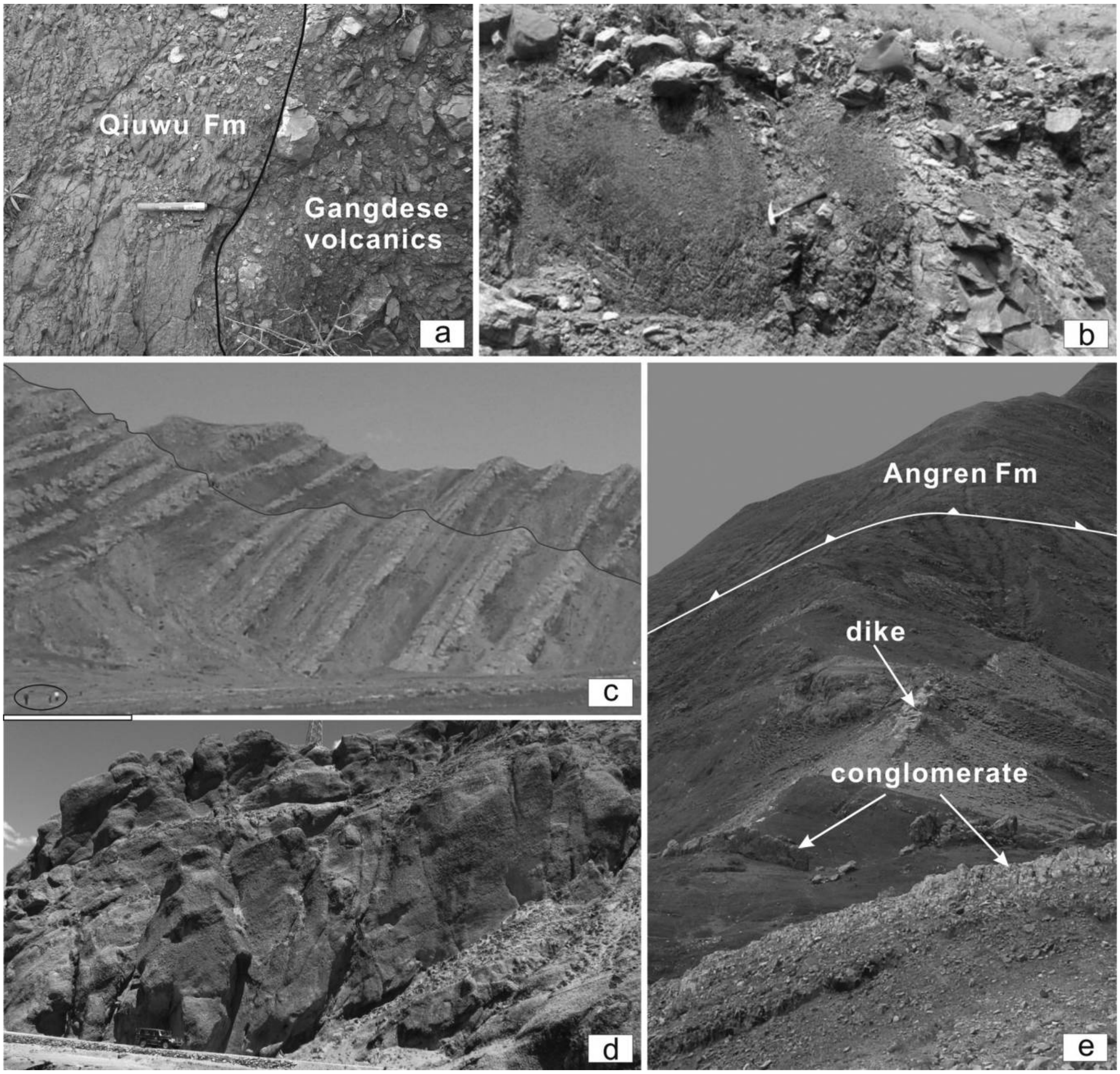

Figure 3. Field photos. *a*, Unconformable contact between the Qiuwu Formation and the underlying Gangdese volcanics; *b*, dark shales and thick bedded sandstones at the lower part of the Qiuwu Formation, Qiabulin section; *c*, panoramic photograph of the Jiangqingze section, showing interbedded thick sandstones and mudrocks; *d*, outcrop of massive conglomerate from the Lower part of the Deri Member, Deri section; *e*, panoramic photograph of the Tunqiong section, showing massive red mudrocks intercalated by thick conglomerate beds. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

qiong Members according to the study by Liu et al. (1996; fig. 2).

Jiangqingze Member. The Jiangqingze Member is well exposed in the Jiangqingze section, where it has a thickness of at least 700 m. The base of the member is covered by Quaternary fluvial sediments, and the top is in fault contact with the Deri Member. A conformable stratigraphic contact with the overlying Deri Member has been observed and documented from the Qiabulin section.

The Jiangqingze Member mainly consists of interbedded sandstones and mudrocks (figs. 2, 3*c*). Sandstone beds are several tens of centimeters to several meters thick, and generally in erosional contact with the underlying mudrocks. Well-rounded pebbles commonly occur at the base of or within sandstone beds. Sedimentary structure in the sandstones includes trough or tabular cross stratification, parallel lamination, and locally ripples. Fining-upward sequences are common. Mudrocks are mostly red and occasionally green, gray, or black, with carbonate nodules, and plant fossils and bioturbation occur.

The Jiangqingze Member is interpreted as having been deposited in a braided fluvial environment. Thick-bedded, upward-fining sandstone beds (St) suggest accumulation in relatively deep, stable fluvial channels. Red-colored mudrocks (Fr, Fl, Fm) represent floodplain deposits, green to dark gray mudrocks (Fl, Fm) represent backswamp or oxbow-lake deposits, and pebble layers (Gt) represent channel lag deposits (table 1).

Deri Member. The Deri Member is over 2000 m thick and consists of pebble to cobble conglomerates with local intercalations of sandstone or red mudrock (figs. 2, 3*d*). The conglomerates occur in beds of 2–10-m thickness, typically with erosional bases, and they are mostly clast supported and moderately well organized, and they include sub- to well-rounded gravel with a maximum clast size of 10–15 cm. Rare sedimentary structures include imbrication and crude cross lamination.

The Deri Member is interpreted as having been deposited in a braided river environment. Lithofacies Gcm, Gmg, Gt, and Sm represent braided river channel deposits, whereas the subordinate lithofacies Fr, Fm, and Fsm represent overbank deposits (table 1).

Tunqiong Member. The Tunqiong Member, which is at least 500 m thick, is generally in fault contact with the Deri Member, but the original stratigraphic relationships can be observed in the Tunqiong section (fig. 2). This member consists of massive or laminated red mudrock with carbonate nodules, and subordinate siltstone and lenticular or massive sandstone and conglomerate (fig. 3*e*). Patches of angular to subangular gravel commonly occur in the massive mudrocks. Sandstone and siltstone beds display small ripples and parallel lamination. Imbrication and cross stratification are occasionally observed in the coarse-grained sandstones and conglomerates.

We interpret the Tunqiong Member as distal alluvial fan deposits. Massive mudrocks with gravels (Fm) represent mud-flow to debris-flow deposits, laminated siltstones (Fl) represent sheet flood deposits, and sandstones (St) and conglomerates (Gt) were deposited in braided channels (table 1).

Age Constraints

Qiuwu Formation. The Qiuwu Formation was previously given a Late Cretaceous to Eocene age based on plant fossils (Guo 1975; Wu 1979; Geng and Tao 1982; Qian 1985). However, the subsequent finding of a palynological assemblage characterized by abundant tricolporate *Quercoidites*, morphologically diverse and low numbers of porate pollen, indicate deposition in the Late Oligocene–Early Miocene (Li 2004). This much younger depositional age was supported by the U-Pb ages of detrital zircons presented in this study, which display a major age cluster between 60 and 40 Ma and a youngest age of 22.5 ± 0.5 Ma. Thus, the depositional age of the Qiuwu Formation should be the latest Oligocene to the earliest Miocene (most probably ~23 Ma), although more precise age constraints are still needed. In the Kailas area, sandstones and tuffs intercalated in lacustrine deposits at the base of the Gangrinboche Conglomerate contain zircon grains with U-Pb ages 26–23 Ma (DeCelles et al. 2011).

Dazhuka Formation. The Dazhuka Formation was previously thought to underlie the Xigaze forearc sequences, and it was therefore assigned to the Early Cretaceous (Wu 1984). Subsequently, the Dazhuka Formation has been assigned to the Middle–Late Eocene, on the basis that it conformably overlies the "Eocene" Qiuwu Formation (e.g., Yin et al. 1988). This issue has been further complicated by the successive findings of Early Cretaceous gastropods in the Tunqiong Member (Liu et al. 1996), pollens of Late Cretaceous age in the Tunqiong Member, and pollens of Early Miocene age in the Jiangqingze Member (Li et al. 2010).

Our field observations confirm that the Dazhuka Formation conformably overlies the Qiuwu Formation, thus it should be younger than the Oligocene. Detrital zircon dating provides additional age constraint, with the youngest zircon grain from the base of the unit at 31 ± 0.5 Ma. The minimum age constraint for the Dazhuka Formation is provided by a felsic dike, dated at 18.3 ± 0.5 Ma (Yin et al. 1994; Aitchison et al. 2002), which cuts across the major north-directed thrust that truncates the top of the Dazhuka Formation. Such evidences, corroborated further by $^{40}Ar/^{39}Ar$ ages of 20–17 Ma obtained from tuffs within equivalent deposits from the Kailas and Dazhuka areas (Aitchison et al.

2009), leads us to the conclusion that the Dazhuka Formation was largely deposited during the Early Miocene (ca. 23–18 Ma).

Provenance Analysis: Methods and Results

An integrated paleocurrent, petrologic, geochemical, and geochronological approach was taken to studying the provenance of the rocks. All analyses were conducted at the State Key Laboratory for Mineral Deposits Research, Nanjing University, China, and the results are given in tables S1–S3, available in the online edition or from the *Journal of Geology* office.

Paleocurrent. Paleocurrents were measured from cross bedding and imbricate structures preserved within sandstone and conglomerate beds. The orientations of trough cross laminations were measured using the method described by DeCelles et al. (1983). Paleocurrent data from the Qiuwu Formation record sediment transport toward the south, indicating a source area located to the north. In the Jiangqingze Member of the Dazhuka Formation, trough cross laminations instead indicate east-west paleocurrents, nearly parallel to the Himalayan belt. Measurements of the limbs of trough cross-lamination sets indicate dominantly westward transport. In the Deri Member, paleocurrent directions range from southwest to northwest, but primarily they indicate transport to the west-northwest. Paleocurrents in the Tunqiong Member were mainly directed toward the northwest (fig. 4).

Conglomerate Clast Counts. At least 100 clasts were counted at each outcrop. The Jiangqingze Member is dominated by intermediate to felsic volcanic gravel, with minor serpentinite, granitoid, and quartzite clasts. Chert is also a major component, particularly in the Qiabulin section. Conglomerates in the Deri and Tunqiong members contain abundant chert and mafic-ultramafic (gabbro, basalt, serpentinite) gravels, with minor granite, volcanic, carbonate, and lithic or quartz-rich sandstone clasts (figs. 4, 5*a*–5*f*).

Sandstone Petrography. Petrographic analyses were performed using the Gazzi-Dickinson method, with at least 400 points counted for each sample (Ingersoll et al. 1984).

Sandstones from the Qiuwu Formation are quartzolithic volcaniclastic (average modal composition Q : F : L = 23 : 9 : 68; figs. 5*g*, 6*a*). Quartz grains are angular to subangular and mostly monocrystalline, clear, and with uniform extinction; some grains display embayments indicative of a volcanic origin. Volcanic lithic fragments are mostly intermediate to felsic in composition. Ultramafic detritus was not observed.

The Jiangqingze Member of the Dazhuka Formation consists of moderately sorted, angular to subrounded feldspatho-quartzolithic volcaniclastic sandstones (Q : F : L = 23 : 20 : 52; figs. 5*h*, 6*a*). Lithic clasts are dominated by intermediate to felsic volcanic fragments, with minor radiolarian chert and ultramafic fragments. Feldspars are more abundant than in the Qiuwu Formation and consist of roughly equal amounts of plagioclase and K-feldspar.

The Deri Member contains quartzolithic sandstones (Q : F : L = 17 : 3 : 80; figs. 5*I*, 6*a*). An abundance of shale/siltstone grains indicates recycling of terrigenous sedimentary units. Compared with the Jiangqingze Member, radiolarian chert and ultramafic fragments are more abundant, whereas volcanic fragments and feldspars are less abundant.

The Tunqiong Member contains quartzolithic sandstones (Q : F : L = 33 : 8 : 69; figs. 5*j*, 6*a*), similar to the Deri Member but with a few samples containing more chert, ultramafic fragments, or quartz. Overall, sandstone petrography records a steady trend, with radiolarian chert and ultramafic fragments increasing in abundance upsection at the expense of volcanic fragments (fig. 6*b*).

Detrital Cr-Spinel Geochemistry. The chemical compositions of Cr-spinels were determined using a JEOL JXA-8800M electron microprobe. Analytical conditions were as follows: accelerating voltage, 15 kV; beam current, 20 nA; beam diameter, 1 μm; and ZAF correction model. The detecting time was 10 s for Al, Fe, and Mg, 20 s for Ti, Mn, Cr, and Ni, and 30 s for Zn. Detection limits were ~200 ppm for all elements.

Cr-spinels from the Qiuwu Formation have a Mg# from 0.27 to 0.60, with a corresponding Cr# mostly varying from 0.42 to 0.84 (0.25 in one grain). TiO_2 contents range from 0.02% to 2.73%. Cr-spinels from three members of the Dazhuka Formation have similar chemical compositions, with Mg# ranging from 0.25 to 0.65, Cr# from 0.29 to 0.94, and TiO_2 from 0 to 2.73% (fig. 7).

Detrital Zircon Geochronology. A total of 551 zircon grains from eight sandstone samples were collected for U-Pb age determinations (fig. A2). Zircon ages were determined using laser ablation–ICP–MS, following the method described by Jackson et al. (2004). For details of the instrumental conditions and processes of data acquisition, see He et al. (2010). Analytical results were calculated using GLITTER 4.4 (Van Achterbergh et al. 2001). Corrections for common Pb were carried out following

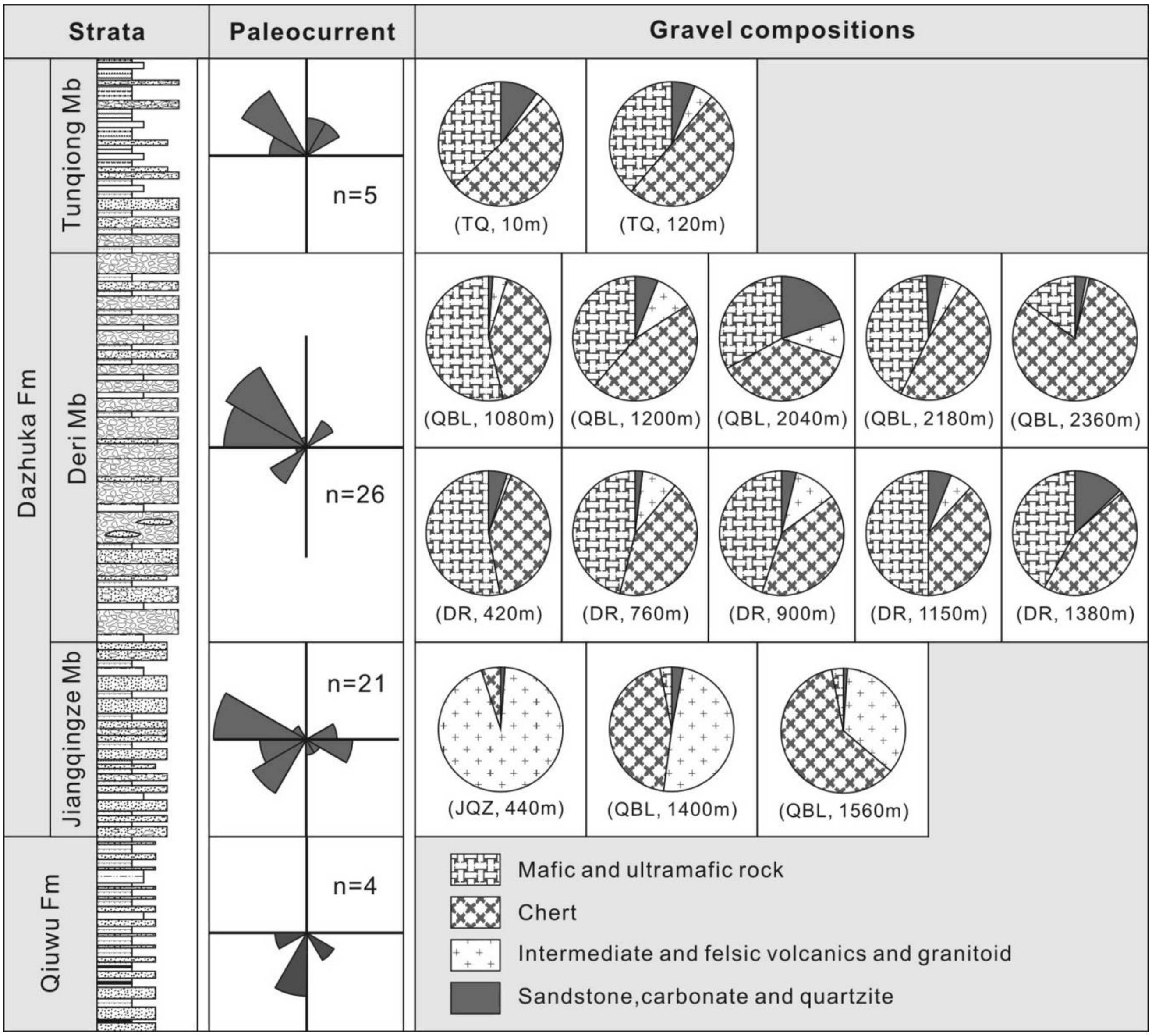

Figure 4. Rose diagrams of paleocurrent directions and pie charts of conglomerate clast compositions. An integrated stratigraphic column is shown on the left. The stratigraphic section and position on the column from which gravel compositions were counted are marked under the pie. QBL = Qiabulin section; JQZ = Jiangqingze section; DR = Deri section; TQ = Tunqiong section. Mb = Member.

Andersen (2002). Age diagrams were drawn up using Isoplot 3.23.

Zircon ages from the Qiuwu Formation mostly cluster around 45 to 70 Ma and 80 to 105 Ma, with peaks at ~48 and ~84 Ma. A few zircons yield Precambrian ages, between 850 and 1150 Ma (fig. 8). The youngest age is 22.5 ± 0.5 Ma. Zircon ages from the Jiangqingze Member are similar to those in the Qiuwu Formation, with major clusters at ~35–60 and ~70–110 Ma, and peaks at ~45 and ~81 Ma (fig. 8). The youngest age is 31 ± 0.5 Ma.

Zircon ages from the Deri Member are different to those above. Paleogene-aged zircons are absent, with the youngest age being 71 ± 2 Ma. The main cluster of ages is between 70 and 130 Ma. Pre-Mesozoic ages are common (ca. 46% of analyzed zircons), with peaks in the Cambro-Ordovician, Neoproterozoic, and Mesoproterozoic (fig. 8). Zir-

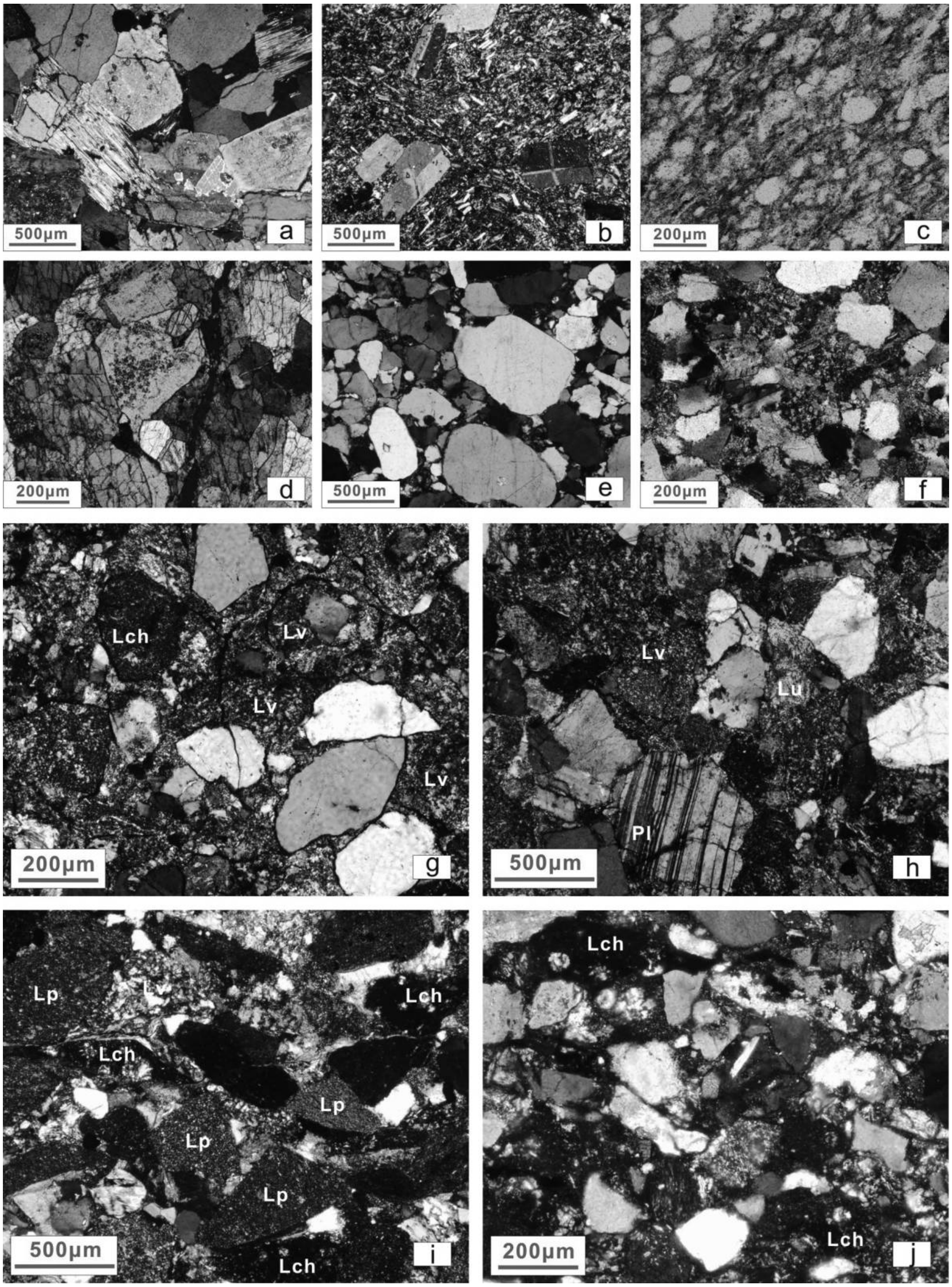

Figure 5. Photomicrograph. Major gravels in the Deri Member: *a*, biotite monzogranite; *b*, trachyte; *c*, radiolarian chert; *d*, gabbro; *e*, quartzarenite; *f*, litharenite. Sandstones from different stratigraphic units: *g*, Qiuwu Formation sandstone; *h*, Jiangqingze Member (Mb) sandstone; *i*, Deri Mb sandstone; *j*, Tunqiong Mb sandstone. Lch = radiolarian chert fragment; Lp = mudrock fragment; Lu = ultramafic lithic fragment; Lv = volcanic rock fragment; Pl = plagioclase. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

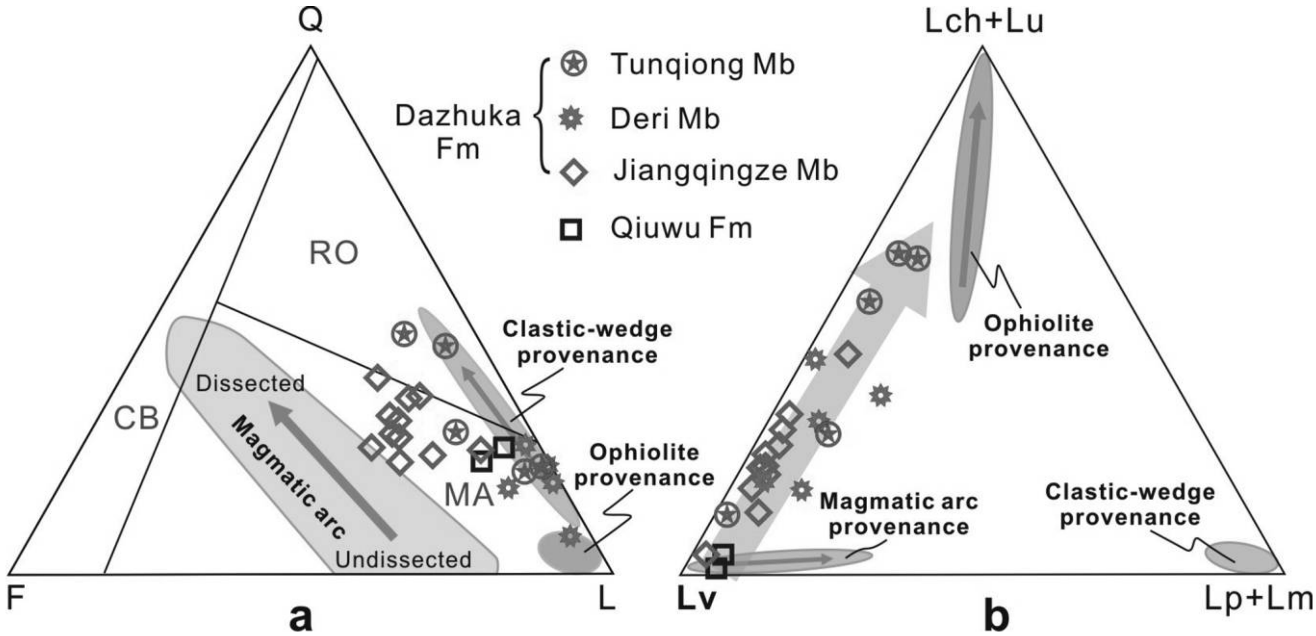

Figure 6. Triplots of sandstone framework compositions. Provenance of modern ophiolite, magmatic arc, and clastic wedge and their exhumation trends (Garzanti et al. 2007) are shown for comparison. Mb = Member; Q = monocrystalline quartz; F = feldspar; L = lithic fragment; Lch = chert fragment; Lm = metamorphic rock fragment; Lp = shale and siltstone fragment; Lu = ultramafic rock fragment; Lv = volcanic rock fragment. Provenance field: CB = continental block provenance; RO = recycled orogen provenance; MA = magmatic arc provenance (Dickinson 1985). A color version of this figure is available in the online edition or from the *Journal of Geology* office.

con ages from the Tunqiong Member also cluster mainly between 70 and 110 Ma, but pre-Mesozoic zircons are rare and some Paleogene zircons occur (47.5 ± 0.9, 48.2 ± 0.9, 57 ± 1, 60 ± 2 Ma; fig. 8).

Discussion

Ophiolitic Source for the Dazhuka Formation. Clasts of basalt, gabbro, serpentinite, as well as radiolarian chert present in the Dazhuka Formation were unequivocally derived from an ophiolitic source. The coarse-grained and immature texture of the Dazhuka Formation suggests that these clasts were derived from proximal sources, most likely the Yarlung-Zangbo ophiolites located nearby to the south (fig. 1*b*). The detrital spinels, reported on above, generally characterized by low TiO_2 contents indicative of a mantle-peridotite source (Kamenetsky et al. 2001), widely overlap in composition with spinels from the Yarlung-Zangbo ophiolites (fig. 7; Wang et al. 2000; Hébert et al. 2003; Bédard et al. 2009). The few Cr-spinels with high Cr# that plot outside the Yarlung-Zangbo peridotite field may have been derived from volcanic rocks or recycled from Xigaze forearc strata (e.g., Guo et al. 2012). We note that the Late Barremian to Early Aptian radiolarian assemblages in chert gravels (Wang et al. 1999*a*; Chan et al. 2005) compare well, also, with the assemblages in cherts from the Yarlung-Zangbo suture zone (Ziabrev et al. 2003).

Wang et al. (2000) proposed that the ophiolitic detritus in the Dazhuka Formation was derived from a Yarlung-Zangbo paleo-ophiolite on the following grounds: (1) the Dazhuka Formation was then thought of as Early Cretaceous age, older than the timing of emplacement of the Yarlung-Zangbo ophiolites; (2) paleocurrents in the Dazhuka Formation mostly indicate transport toward the south; and (3) the chemical compositions of detrital Cr-spinels and ultramafic pebbles seemed to differ from the then known Yarlung-Zangbo mantle rocks. However, new data have invalidated all these grounds. Firstly, paleontological and geochronological data indicate that the Dazhuka Formation was deposited in the Early Miocene, much later than the ophiolite emplacement (e.g., Ding et al. 2005). Second, our paleocurrent data set indicates a dominantly west-northwestward paleocurrent direction. Thirdly, mantle rocks geochemically analogous to ultramafic pebbles in the Dazhuka Formation are now documented in the Yarlung-

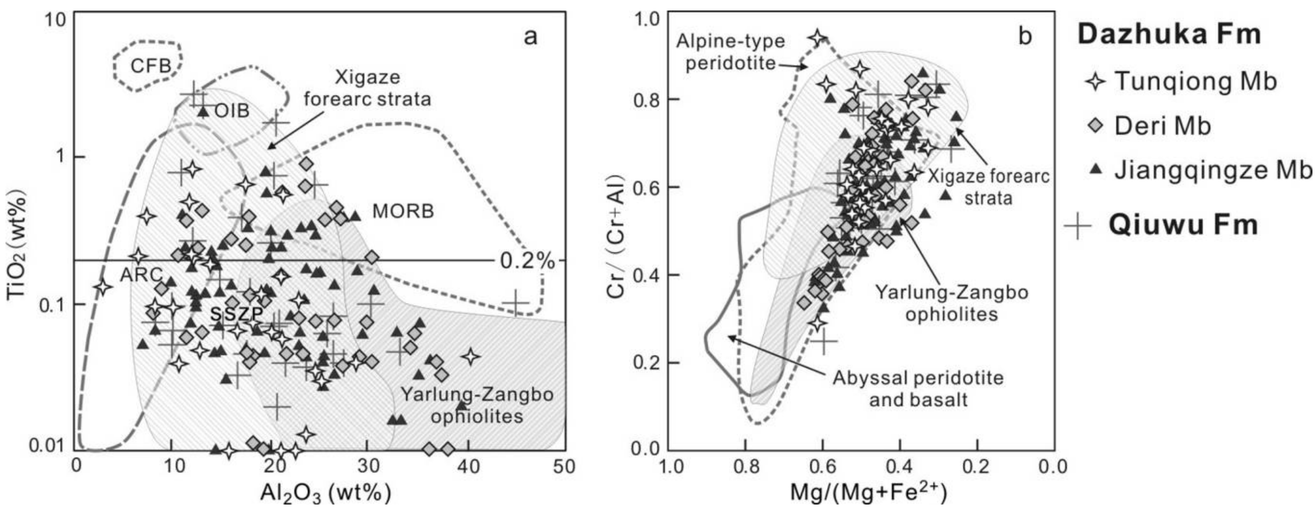

Figure 7. Tectonic setting discrimination plots for detrital Cr-spinels from the Qiuwu and Dazhuka Formations. *a*, TiO_2 versus Al_2O_3 diagram; tectonic fields are after Kamenetsky et al. (2001). CFB = continental flood basalt; MORB = mid-ocean ridge basalt; OIB = ocean island basalt; SSZP = suprasubduction zone peridotite. *b*, Cr# versus Mg# diagram; tectonic fields are after Irvine (1974) and Dick and Bullen (1984); Mb = Member. Field for the Yarlung-Zangbo ophiolite is from Wang et al. (2000), Hébert et al. (2003), and Bédard et al. (2009); field for the Xigaze forearc strata is from Guo et al. (2012). A color version of this figure is available in the online edition or from the *Journal of Geology* office.

Zangbo ophiolites (e.g., Hébert et al. 2003; Bédard et al. 2009). Therefore, we conclude that ophiolitic clasts in the Dazhuka Formation were derived from the Yarlung-Zangbo ophiolites, instead of a Yarlung-Zangbo paleo-ophiolite source as proposed by Wang et al. (2000).

Provenance Changes through Time. The Qiuwu sandstones are dominated by volcanic detritus typical of an undissected magmatic-arc provenance (fig. 6*a*; Dickinson 1985; Garzanti et al. 2007). The volcanic rocks that originally overlay the Gangdese batholiths are the most obvious source, and this would be consistent with the paleocurrent data that indicate a northern source (fig. 4). Detrital zircon ages from the Qiuwu Formation show age patterns that are typical of the Gangdese arc (e.g., Chu et al. 2006; Wen et al. 2008; Ji et al. 2009; Zhu et al. 2011; fig. 8). The few older zircons may either have been recycled from sedimentary rocks of the Lhasa terrane (e.g., Leier et al. 2007) or have been derived from Gangdese magmatic rocks as inherited zircons (Chu et al. 2006; Zhu et al. 2011). A mafic/ultramafic source is not indicated for the Qiuwu Formation. The Cr-spinels present may have been derived from the Lhasa terrane, because Cr-spinels with similar compositions are found in Xigaze forearc strata derived primarily from the Lhasa Terrane (Guo et al. 2012).

The first indisputable supply from the Yarlung-Zangbo suture zone in the south is recorded by the Jiangqingze Member of the Dazhuka Formation, as indicated by radiolarian chert and serpentinite fragments. During deposition of the Jiangqingze Member, however, detritus was still being derived dominantly from the Gangdese magmatic arc in the north, as indicated by abundant volcanic fragments, feldspars, and young-aged zircons (~35–110 Ma). As the Qiuwu Formation sandstones, the Jiangqingze Member sandstones plot within the "magmatic arc" provenance field (fig. 6*a*). A relative enrichment in quartz and feldspar probably indicates progressive unroofing of the Gangdese arc during deposition of the Jiangqingze Member.

An increasing supply of material from the Yarlung-Zangbo suture zone is recorded in the overlying Deri and Tunqiong members, where chert and mafic-ultramafic clasts represent at least 40% of the total grains in the sandstones and 70% in the conglomerates (figs. 4, 6*b*). Moreover, gravels of volcaniclastic sandstone, comparable to Xigaze forearc strata, are present, as are quartzose sandstone and carbonate gravels that were probably derived from Tethys Himalayan strata. Conversely, these two members contain only minor amounts of granitoid and volcanic clasts from the Gangdese arc.

A prominent flux of detritus from the south also explains the changes in detrital zircon age spectra that are recorded in the Deri and Tunqiong mem-

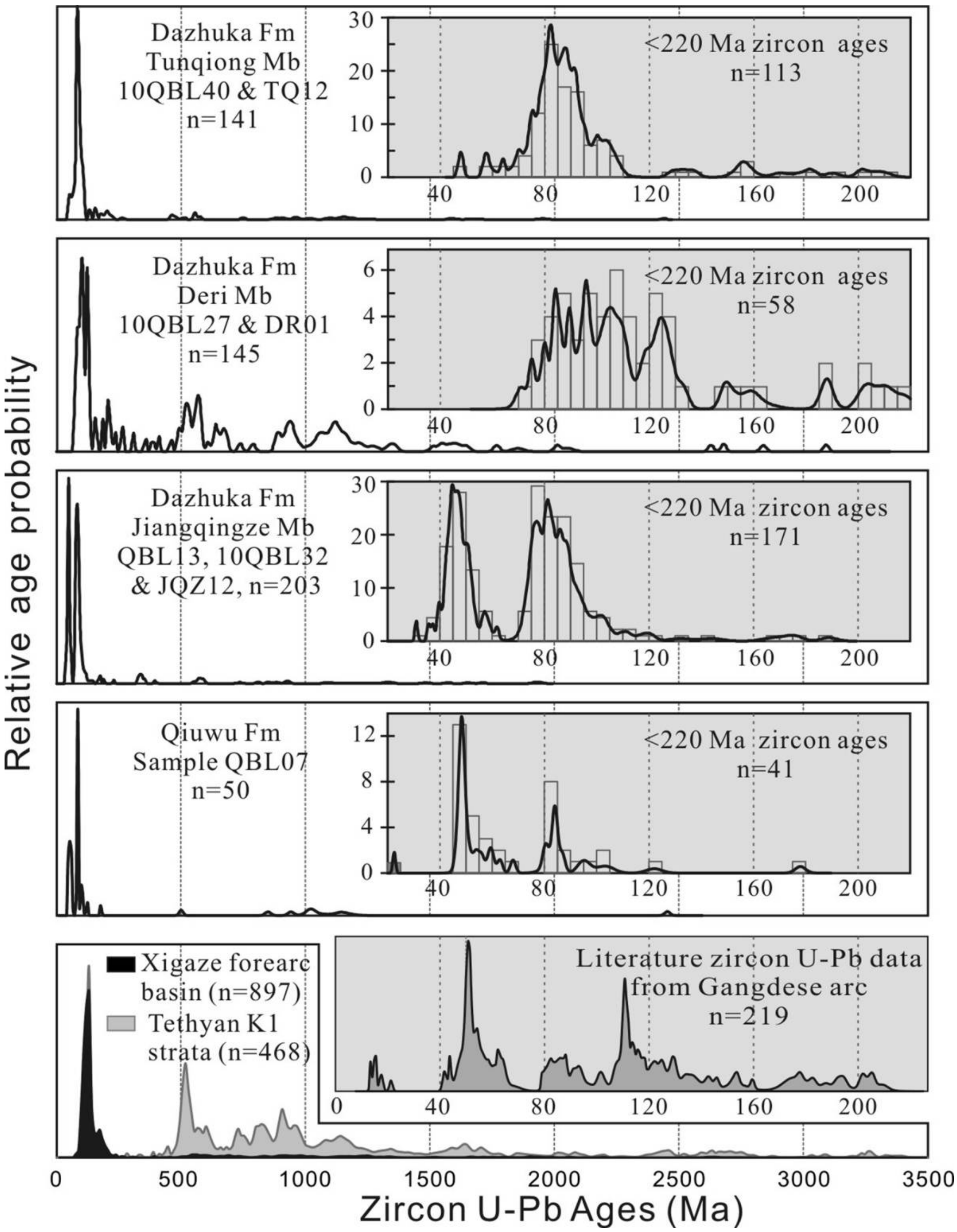

Figure 8. Relative U-Pb age probability for detrital zircons from the Qiuwu and Dazhuka Formations. Also shown for comparison are data from the Tethys Himalayan Lower Cretaceous strata (Hu et al. 2010, 2012; Wang et al. 2011), Xigaze forearc strata (Wu et al. 2010; Aitchison et al. 2011; and our unpublished data), and the Gangdese magmatic rocks (Chu et al. 2006; Wen et al. 2008 and reference therein); Ji et al. 2009. Mb = Member.

bers, with a dearth of Cenozoic ages and common pre-Mesozoic ages (fig. 8). Consistent with the increasing proportion of recycled detritus indicated by detrital modes, most zircon grains in the Deri and Tunqiong members are interpret as having been recycled, with Mesozoic and pre-Mesozoic zircons largely derived from Xigaze forearc and Tethyan strata, respectively.

Overall, the Upper Oligocene–Lower Miocene Gangrinboche Conglomerate in the Xigaze area records a progressive change in provenance, from the Gangdese arc in the north to the Yarlung-Zangbo suture and the Himalayan orogen in the south. Notably, clasts from the Gangdese arc and the Yarlung-Zangbo suture zone coexist in the Dazhuka Formation.

Depositional Model for the Gangrinboche Conglomerate. Several depositional models have been proposed for the Gangrinboche Conglomerate. Yin et al. (1999), based on their studies in southwest and southeast Tibet (the Kailas and Zedong areas, respectively), proposed that the lower part of the Gangrinboche Conglomerate (mainly derived from the north) was associated with the development of the Gangdese Thrust, whereas its upper part (mainly derived from the south) was mainly associated with the development of the Great Counter Thrust. Although this model provided a plausible mechanism for both basin formation and the uplift of source areas, Aitchison et al. (2003) asserted that the inferred Gangdese Thrust does not exist. Aitchison et al. (2002, 2007) interpreted the Gangrinboche Conglomerate as a continental molasse developed in response to the initial India-Asia collision. Based partly on this interpretation, they suggested that the India-Asia collision did not begin until the Eocene-Oligocene boundary (~34 Ma). As discussed in Garzanti (2008), this notion is at odds with other stratigraphic and petrologic evidences. The recent study by DeCelles et al. (2011) in the Kailas area indicates that the lower part of the Gangrinboche Conglomerate was deposited in an extensional or transtensional basin, whereas contraction took place during deposition of the upper part. They further suggested that southward rollback and subsequent break-off of the underthrusting Indian continental lithosphere might have provided the geodynamic control for the basin development.

Although tectonic interpretations are still controversial, the geological significance of the Gangrinboche Conglomerate has been progressively clarified by a succession of studies (e.g., Yin et al. 1999; Aitchison et al. 2000, 2002; Li et al. 2010; DeCelles et al. 2011). Any tectonic model attempting to explain the deposition of the Gangrinboche Conglomerate should consider that (1) the unit stratigraphically overlies the Gangdese magmatic rocks and is commonly truncated at the top by a north-directed thrust; (2) a similar stratigraphy has been documented along strike over 1500 km; (3) lacustrine rocks locally underlie the main conglomerate facies; (4) detritus at the base of the Gangrinboche Conglomerate is entirely derived from the north, whereas clasts derived from the south appear upsection and become progressively more abundant; and (5) deposition of the Gangrinboche Conglomerate took place about 30 m.yr. after the onset of the India-Asia continental collision.

As referred to in "Introduction," numerous prominent tectonic and magmatic events occurred in the Himalaya-Tibetan Orogen during the Late Oligocene–Early Miocene. The coincidence in the timing of these events with deposition of the Gangrinboche Conglomerate suggests the possibility of a common causal link. In the following, and based on our new data sets, we illustrate our preferred model for deposition of the Gangrinboche Conglomerate (fig. 9).

Late Oligocene (~30–26 Ma, Fig. 9a). As a result of the India-Asia collision and subsequent crustal shortening, the Yarlung-Zangbo suture zone has been exposed. Detritus eroded from the Yarlung-Zangbo ophiolites and the Xigaze forearc strata was accumulated south of the Yarlung-Zangbo suture belt, such as recorded by the Liuqu Conglomerate (Wang et al. 2010; Leary et al. 2012). No sediment was deposited at the south flank of the Gangdese magmatic arc.

Latest Oligocene–Earliest Miocene (~26–23 Ma, Fig. 9b). Lake and delta sediments were deposited at the base of the Gangrinboche Conglomerate along the south edge of the Gangdese arc. Tectonic extension, and the consequential rapid subsidence, which possibly resulted from southward rollback of the subducted Indian slab or oblique slip along the suture zone, is an effective way of generating a series of lakes along the southern margin of the Gangdese belt (DeCelles et al. 2011). Alternatively, damming of rivers originally flowing transversely across the suture zone and the consequential lake development might have resulted from the Himalayan uplift. In this initial stage, detritus was entirely derived from the Gangdese arc, suggesting that the Yarlung-Zangbo suture zone was still characterized by low elevation.

Early Miocene (~23–18 Ma, Fig. 9c). Rapid uplift and erosion of Himalayan Orogen and the Yar-

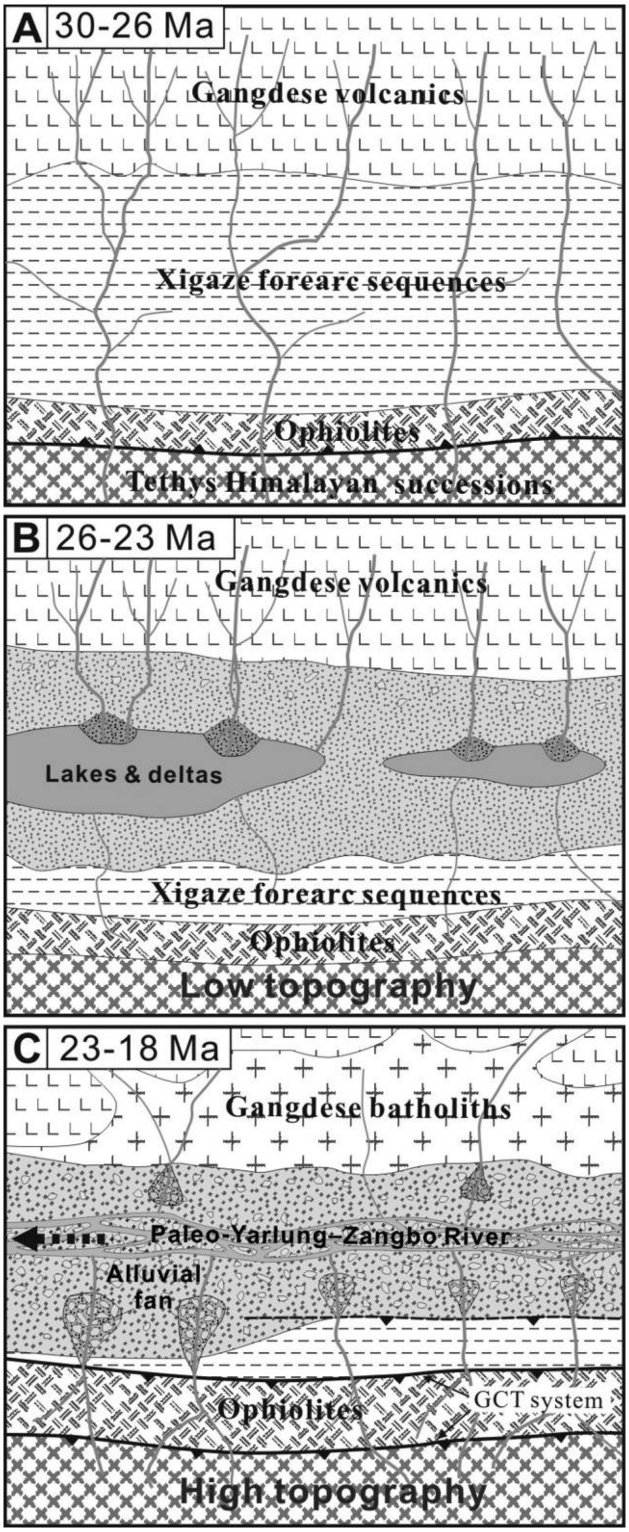

Figure 9. Sketched paleogeographic map show the Late Oligocene–Early Miocene depositional and geomorphological evolution along the Yarlung-Zangbo suture, indicating initiation of the paleo-Yarlung-Zangbo river. GCT = Great Counter Thrust. See the text for details.

lung-Zangbo suture occurred at this time (e.g., Harrison et al. 1992; White et al. 2002), accompanied by the development of the South Tibetan Detachment System and the Main Central Thrust (Yin 2006). Detritus from the Yarlung-Zangbo ophiolites, the Xigaze forearc basin, and possibly the Tethyan Himalaya progressively increased with time, and accumulated in the Gangrinboche Conglomerate basin. Rapid uplift of the Himalayas also led to changes in sedimentary facies from low-energy delta and fluvial environments in the early stages to high-energy braided river and alluvial fan environments in the later stages.

The prominent tectonic, magmatic and sedimentary events documented in the Early Miocene are best explained by the transition from the "soft collision" to the "hard collision" of the Himalayan Orogeny, initiated by the arrival of thicker non-subductable Indian crust at the subduction zone (Garzanti 2008). In turn, this might have resulted in the delamination of the subducting Indian lithosphere, which would have fostered the sudden rapid uplift of the Himalayan belt as well as the onset of ultrapotassic and adakitic magmatism in Tibet (Chung et al. 2003, 2005; DeCelles et al. 2011). Deposition of the Gangrinboche Conglomerate ceased by ~18 Ma, which might have been the result of continuous uplift of the orogenic belt or northward propagation of the Great Counter Thrust (Ratschbacher et al. 1994; Quidelleur et al. 1997; Yin et al. 1999).

Initiation of the Axial Yarlung-Zangbo River Drainage. The Yarlung-Zangbo River is the longest longitudinal river system in the Himalayas. The timing of its initiation is a vital factor in understanding the regional drainage evolution, and in assessing the interaction between tectonic and erosional processes. The Late Oligocene–Miocene continuous sedimentary records in the Xigaze area and our original sedimentologic and provenance data presented in this study provide valuable constraints on characterizing and dating the initiation of the axial paleo-Yarlung-Zangbo River system.

In the Qiuwu Formation, paleocurrents were southward, and sediment was derived entirely from the Lhasa terrane, with no evidence of mixed detritus from Indian and Asian sources, such as should characterize an axial river system. We can conclude, therefore, that a paleo-Yarlung-Zangbo River system did not exist during the Late Oligocene. The first record of sediment transport along the axis of the orogen is at the base of the Dazhuka Formation (the lowermost Miocene Jiangqingze Member), of which the strata were deposited in a braided fluvial environment with axial paleocurrents, and clasts were derived from both the south (from the Yarlung-Zangbo suture zone) and the north (from the Gangdese arc). Hence, it indicates that the timing for initiation of a paleo-Yarlung-Zangbo River system was the earliest Miocene, at ~23 Ma. In the western Himalayas, the paleo-Indus River was initiated nearly at the same time as initiation of the paleo-Yarlung-Zangpo River (Sinclair and Jaffey 2001; Henderson et al. 2010, despite that data from the Indus fan indicate its inception could be as early as the Middle Eocene (Clift et al. 2001). The quasi-contemporaneous development of major longitudinal drainage systems is fully consistent with initial rise of the Himalayas in the Early Miocene as a mountain belt of high elevation and relief (Yin 2006).

Paleocurrent data from the Dazhuka Formation indicate dominantly west- to northwestward sediment transport (fig. 4). This implies that the paleo-Yarlung-Zangbo River once flowed westward, in contrast with the modern eastward-flowing Yarlung-Zangbo River. We propose that the westward-flowing paleo-Yarlung-Zangbo River might have connected with the paleo-Indus River to form a united longitudinal axis of sediment transport. Alternatively, the river might have turned southward to the west of our study area, possibly connected with an antecedent transverse river that cut across the rising Himalayan belt. Reversal of the paleo-Yarlung-Zangbo and formation of the modern Yarlung-Zangbo River must have taken place subsequently. Possible causes of this drainage reversal include movement along the Karakorum Fault (e.g., Murphy et al. 2000), differential tectonic uplift along strike (Yin 2006), and river capture processes (e.g., Liang et al. 2008; Cina et al. 2009; Zhang et al. 2012). It is interesting to realize that uplift and focused erosion of the Eastern Namche Barwa syntaxis, and development of the Yarlung-Zangbo Gorge mainly occurred within the last 4 Ma (Burg et al. 1998; Seward and Burg 2008), much later than the initiation of the paleo-Yarlung-Zangbo River. The relationships of the drainage change of the Yarlung-Zangbo River with the exhumation of the Eastern Namche Barwa Syntaxis remain to be investigated.

Conclusions

The Gangrinboche Conglomerate in southern Tibet recorded a crucial stage of the Himalayan Orogeny. Sedimentologic and provenance studies of the Gangrinboche Conglomerate in the Xigaze area, comprising the Qiuwu and Dazhuka Formations, allow the following conclusions.

1. The Qiuwu Formation was deposited during the latest Oligocene to the earliest Miocene (~23 Ma) and consists of sandstones and variously colored mudrocks that have been deposited in lake and deltaic environments. Whereas, the Dazhuka Formation was deposited at the Early Miocene (~23–18 Ma), and comprises dominantly coarse-grained clastic rocks deposited mainly in braided river systems.

2. Provenance analyses show that detritus of the Qiuwu Formation were derived entirely from the Gangdese magmatic arc to the north. By contrast, the Dazhuka Formation records a progressive increase in detrital contributions from the Yarlung-Zangbo ophiolitic suture and the Himalayan belt to the south.

3. Paleocurrent data from the Dazhuka Formation show axial directions, which were mainly directed westward. This together with the coexistence of clasts derived both from the Gangdese arc to the north and the Yarlung-Zangbo suture zone to the south in the Dazhuka Formation, indicate that a paleo-Yarlung-Zangbo River that flowed toward the west was established at the very start of the Miocene.

4. Our data from the Tibetan side of the Himalayan orogen is consistent with data from coeval deposits in the Himalayan foreland basin and indicate inception of rapid uplift and erosion of the Himalayan orogenic belt during the earliest Miocene. Onset of rapid Himalayan uplift and the coeval tectonic and magmatic events are best explained by a transition from the "soft collision" stage to the "hard collision" stage of the Himalayan Orogeny, possibly in association with the detachment of the subducting Indian lithosphere.

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