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Large rivers and orogens: The evolution of the Yarlung Tsangpo–Irrawaddy system and the eastern Himalayan syntaxis

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ABSTRACT

The eastern Himalayan syntaxis has experienced some of the highest rates of deformation and erosion in the orogen during the Late Cenozoic, and the Yarlung Tsangpo, Brahmaputra, Irrawaddy, Salween, and Mekong rivers are the key erosional systems in that region. The Yarlung Tsangpo drains southern Tibet and the deep Siang River gorge through the eastern Himalayan syntaxis before joining the Brahmaputra in northeastern India. It has been proposed that the Yarlung Tsangpo drained into other large rivers of southern Asia, such as the Irrawaddy, Salween and Red River. We have used uranium/lead dating and hafnium measurements of detrital zircons from Cenozoic sedimentary deposits in Central Myanmar to demonstrate that the Yarlung Tsangpo formerly drained into the Irrawaddy River in Myanmar through the eastern syntaxis, and that this ancient river system was established by (at least) the Middle–Late Eocene. The Yarlung Tsangpo–Irrawaddy river disconnected in the Early Miocene driven by increased deformation in the eastern syntaxis and headward erosion by tributaries of the Brahmaputra. Our results highlight the significance of the sedimentary record of large orogen-parallel rivers and provide key chronological constraints on landscape evolution during the Early Miocene phase of the Himalayan orogeny.

1. Introduction

Recent research on large Asian river systems (Brookfield, 1998; Zeitler, 2001; Clark et al., 2004; Clift et al., 2006; Finnegan et al., 2008; Booth et al., 2009) has focused attention on their role in tectonics and tested how influential rivers are in controlling the location and magnitude of deformation. The significance of the coupling between tectonics and riverine erosion is well demonstrated in the eastern syntaxis of the Himalayas, where a proportionally small, but rapidly uplifting area of the orogen contributes half of the sediment budget for the modern Brahmaputra River (Stewart et al., 2008). The evolution of the Yarlung Tsangpo, prior to its capture by the Brahmaputra, has been debated for over a century. Brookfield (1998) and Clark et al. (2004), building on earlier publications by Burrard and Hayden (1907) and Seeber and Gornitz (1983), have stressed that the timing of river capture events throughout the Himalayas and southeast Asia is particularly relevant to understanding the mechanics and feedback between focused uplift and river erosion (Booth et al., 2009). Clark et al. (2004) suggested that the Yarlung Tsangpo, Irrawaddy and Salween (Fig. 1) were tributaries to the Red River before the onset of Himalayan collision. Hoang et al. (2009) used U/Pb dating and εHf isotopic values of detrital zircons from modern Red River samples and Middle–Upper Miocene sedimentary rocks within the catchment of the modern Red River to demonstrate that there was no connection between the Irrawaddy and Red Rivers after the Late Miocene, and concluded that it is unlikely that one ever existed. We have obtained new U/Pb and εHf isotopic data of the detrital zircons from Cenozoic deposits of the Central Myanmar Basin (Fig. 1) that demonstrates that a Yarlung Tsangpo–Irrawaddy system existed as long ago as the Late Eocene, and that the Yarlung Tsangpo–Irrawaddy connection was broken in the Early Miocene, coincident with deformation along the strike slip Jiali–Parlung and Gaoligong faults in the eastern syntaxis (Lin et al., 2009) and the Sagaing Fault in Myanmar (Mitchell et al., 2007). Our results provide constraints on the rate of landscape response to deformation in the syntaxis and temporal constraints on the earliest evolution of the modern Yarlung Tsangpo–Brahmaptura river system that drains Namche Barwe in the eastern syntaxis (Stewart et al., 2008).

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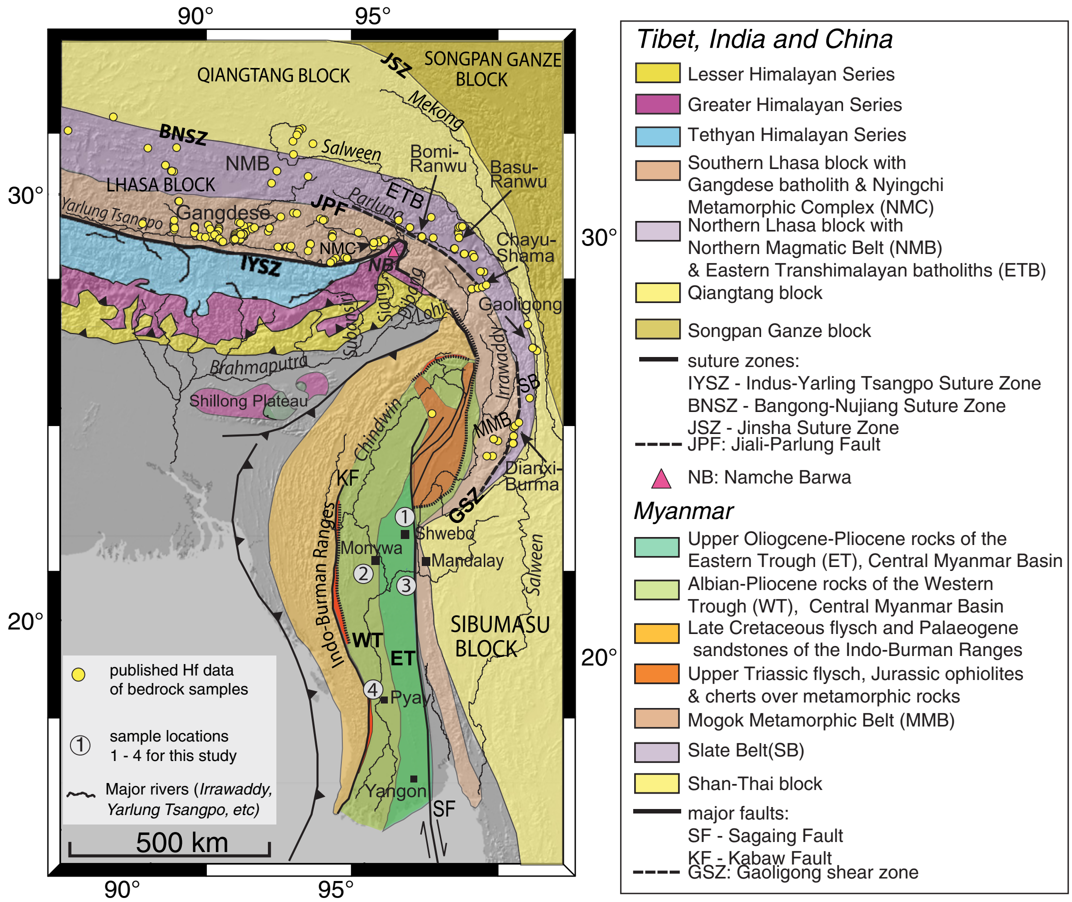

Fig. 1. Simplified geological map showing major terranes, terrane boundaries and geological units in the eastern Himalayan region and Myanmar, and major modern rivers. Locations of published U/Pb and Hf data used in this paper are shown (see text for references). Locations 1–4 in the Central Myanmar Basin represent the sampling areas for the ten samples presented in this paper. Figure modified from Mitchell et al. (2012) and Cina et al. (2009).

2. Background

The Central Myanmar Basin is a forearc basin formed during northeastward subduction of the Bengal oceanic crust beneath Myanmar and is comprised of Eocene-Quaternary sedimentary and volcanic rocks (Mitchell, 1993). Seismic reflection data reveal that the basin is composed of a Western Trough with up to 15 km of Eocene–Pliocene sedimentary rocks, while less than 8 km of primarily Miocene–Pliocene rocks overlie the basement rocks of the Burma plate in the Eastern trough (Bertrand and Rangin, 2003). The Kabaw Fault bounds the Central Myanmar Basin on the west (Fig. 1) and separates it from the Late Mesozoic–Neogene carbonate and flysch forearc-accretionary prism and plutonic rocks of the Indo-Burman Ranges (Bender, 1983; Mitchell, 1993; Allen et al., 2008). The Mogok Metamorphic Belt and Sibumasu block border the basin to the east, and south of Mandalay this boundary is clearly defined by the right-lateral Sagaing Fault (Fig. 1). The Mogok Metamorphic Belt occurs as narrow deformational zones (30–40 km wide) between the Central Myanmar Basin and the Shan Plateau of the Sibumasu block (Fig. 1), and is bounded by the Slate Belt in northeastern Myanmar (Mitchell et al., 2007). These regions contain intrusive rocks that are part of the Late Jurassic–Eocene magmatic arc which can be traced north through the eastern Himalayan syntaxis and into the Transhimalayan rocks of Tibet (Mitchell et al., 2007; Searle et al., 2007; Chiu et al., 2009; Mitchell et al., 2012). All of the magmatic arc rocks have similar chronologies, but differing geochemistry: the Gangdese is an I-type batholith, whereas the intrusive rocks of the eastern Transhimalayan, Mogok Metamorphic Belt and western Thailand (Fig. 1) are predominately S-type (Bertrand et al., 1999; Mitchell et al., 2007; Chiu et al., 2009; Ji et al., 2009; Searle et al., 2012).

During Late Jurassic–Cretaceous time, the West Burma block docked with Asia resulting in northwards-directed thrusting of ophiolites that are compositionally equivalent to the Yarlung ophiolite zone in Tibet (Mitchell, 1993). The 90° clockwise rotation of the Bangong–Nujiang and Indus–Yarlung Tsangpo suture zones reflects the cumulative Cenozoic deformation of SE Asia (Fig. 1) and 40° of this rotation is thought to have occurred since the Early Miocene (Tapponnier et al., 1982). The right lateral Sagaing Fault runs from north to south and is the boundary between the Central Myanmar Basin and the Mogok Metamorphic Belt (Fig. 1); total offset is debated but ranges from 330 km (Curray, 2005) to as much as 1000 km (Hla Maung, 1987; Mitchell, 1993; Mitchell et al., 2012), and most of this has occurred since the Miocene (Pivnik et al., 1998; Morley, 2002).

Here we report on the results of our isotopic fingerprinting of the sedimentary rocks in the Central Myanmar Basin. We have measured the U–Pb ages and εHf values for detrital zircons from a suite of Eocene, Oligocene, and Miocene units in order to investigate whether a Yarlung Tsangpo–Irrawaddy connection existed during the Eocene and Oligocene, and if so, to constrain when that connection was broken. Our study complements and builds upon previous research that has documented the chronology of magmatic events and dating of detrital zircons from southern Tibet, the Eastern syntaxis, and Myanmar (Bodet and Scharer, 2000; Mo et al., 2005; Chu et al., 2006; Liang et al., 2008; Chiu et al., 2009; Chung et al., 2009; Ji et al., 2009; Mo et al., 2009; Zhu et al., 2009a,b; Zhang et al., 2010; Chu et al., 2011; Guan et al., 2011; Guo et al., 2011; Zhu et al., 2011; Guan et al.,

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2012; Guo et al., 2012; Ji et al., 2012). A number of studies on igneous and metamorphic rocks in the eastern Transhimalayan syntaxis region and within the Mogok Metamorphic Belt and Slate Belt provide the bedrock U/Pb and εHf signatures from this part of the orogen which is within the current Irrawaddy River catchment area (Liang et al., 2008; Chiu et al., 2009; Shi et al., 2009; Zhu et al., 2009c; Xu et al., 2012). Liang et al. (2008) presented U/Pb and εHf data for zircons from three Transhimalayan batholiths in Tibet and Myanmar, and detrital zircons from a Miocene deposit in Myanmar, and used the presence of high positive εHf values of the Gangdese batholith in Tibet as evidence that the Yarlung Tsangpo was connected to the Irrawaddy in the Late Miocene.

2.1. Sample collection

We collected a total of ten rock samples within the Central Myanmar Basin from fluvial and estuarine sandstones of Middle–Late Eocene (Pondaung Formation), Oligocene (Padaung Formation), and Miocene (Taungtalon, Shwetaung, Moza, Obogon Formations) age (Figs. 1, 2). The Eocene shoreline was located at a similar latitude to Mandalay (Aung Khin and Kyaw Win, 1968). In the Eastern Trough, we collected two samples of the Pondaung Formation from northeast of Shwebo, and one sample each from three Miocene units located south of Mandalay (Fig. 1). Three Oligocene-aged samples were collected from the northern end of the Mimbu Basin near Monywa in the Western Trough, and two more Miocene samples were collected west of Pyay (Fig. 1). Different localities were required to collect the samples because there is a widespread unconformity spanning the Oligocene in the Eastern Trough of the Central Myanmar Basin, and Eocene and Miocene sedimentary rocks are well exposed to the north and south of Mandalay, respectively (Figs. 1, 2). More details of the samples are provided in the Supplementary Materials.

2.2. Methods

We separated zircons from all samples and combined U/Pb and Lu/Hf methods to discriminate between the potential source areas for the Cenozoic sedimentary rocks of the Central Myanmar Basin. Zircon is a common accessory mineral in felsic igneous rocks, and its high crystallization temperature, hardness and inertness mean that it is also found in metamorphic and sedimentary rocks. Zircon contains up to 1% uranium and up to 2% hafnium, and the isotopes of these elements are used in radiometric dating (U/Pb system) and to quantify the contributions of the mantle to crustal rocks (Lu/Hf system), thereby providing additional information on the source of the zircon (Bodet and Scharer, 2000). Detrital zircon geochronology is a

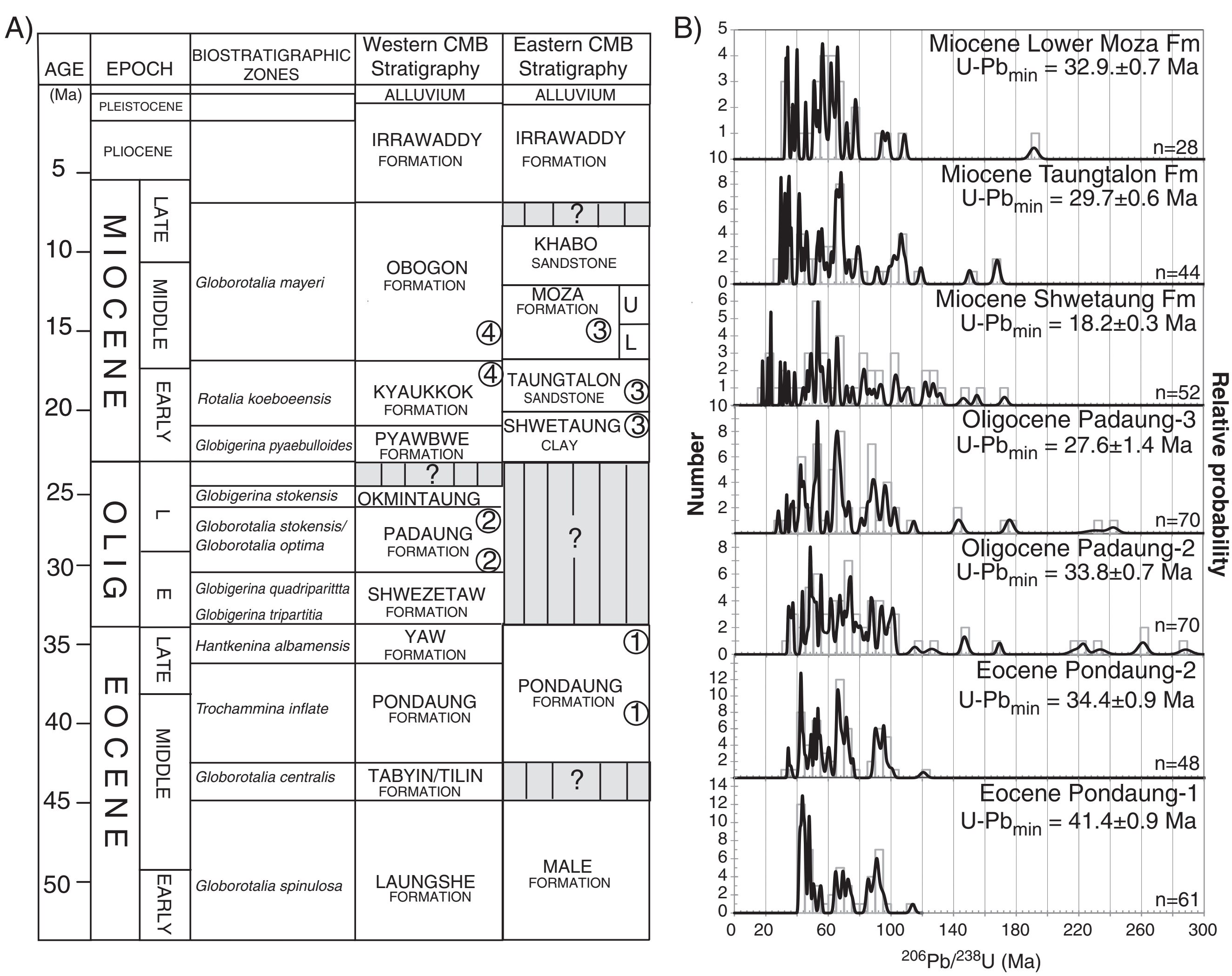

Fig. 2. Stratigraphy and U/Pb data of detrital zircons. A. Cenozoic stratigraphy of the Central Myanmar Basin (biostratigraphy from Bender, 1983) and the intervals sampled during this study. Numbers refer to locations shown in Fig. 1. B. U/Pb data for seven of the Cenozoic samples collected. Only data less than 300 Ma are shown. See Table S1 for the full tabulated dataset.

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well-established set of techniques primarily used for determining provenance in sedimentary rocks. All U/Pb dating and Lu/Hf measurements were made at the NERC Isotope Geosciences Laboratory (NIGL) in Keyworth with a Nu Plasma Laser Ablation–Multi-Collector-Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICPMS) using high sensitivity methods on imaged zircons and appropriate reference materials. Sedimentary rock samples were prepared at the University of St Andrews. They were crushed and zircons were picked from non-magnetic sediment fractions after density separations on a Wilfley table and in heavy liquid, and compositional separation using a Frantz magnetic separator. Zircon crystals were mounted on tape, set in epoxy resin, and polished. Both cathodoluminescence and backscatter images were taken of all grains to aid identification of mineral zoning and overgrowths, and to help with the selection of areas suitable for laser ablation. U/Pb measurements were conducted first, followed by Lu/Hf measurements on a sub-set of zircons for each sample. More details on sample preparation and measurement, and the complete U/Pb and Lu/Hf datasets are presented in Supplementary Materials (Tables S1 and S2). All quoted ages are calculated using $^{206}Pb/^{238}U$ with a 2σ uncertainty.

3. Results

In order to test whether zircons derived from the Gangdese batholith, or other Lhasa terrane rocks, are contained in the sedimentary rocks of central Myanmar, and to establish whether a Yarlung Tsangpo–Irrawaddy river existed during Eocene to Miocene time, we compare our detrital zircon data with published U/Pb and Hf data for Transhimalayan batholiths in the Lhasa terrane, the eastern syntaxis, and within the current catchment of the Irrawaddy River in northeastern Myanmar (Fig. 1). The U/Pb ages of detrital zircons from our Cenozoic samples all contain relatively small proportions (<10%) of Proterozoic- and Paleozoic-aged grains (Figs. 2, S2 and Table S1), but the dominant age populations reflect large contributions of rocks involved in the closure of the Tethyan seaway. Consequently, we focus on data for the last 300 Ma. Our oldest Cenozoic sample (Pondaung-1; Pondaung Formation) is Middle to Late Eocene in age and its youngest concordant detrital zircon is 41.4 ± 0.9 Ma (Fig. 2), which provides a maximum age for this sample. Absolute depositional ages for the upper Pondaung Formation are based on a fission track date of 37–38 Ma for zircons extracted for an ash bed located southwest of Monywa (Fig. 1), which is associated with primitive anthropoid fossils (Tsubamoto et al., 2002; Beard et al., 2009). New LA-ICP-MS U/Pb ages of zircons extracted from the same tuff bed (Khin Zaw et al., 2013) suggest a slightly older timing for deposition (40.2 ± 0.5 Ma). Our detrital zircon data for Pondaung-1 have three distinct age peaks and a mode at ~45 Ma. The Oligocene samples from the Padaung Formation have a broad range of U/Pb ages less than 100 Ma, and based on the youngest concordant zircon has a minimum age of 27.6 ± 1.4 Ma (Fig. 2). The Early Miocene Shwetaung Formation is dominated by U/Pb ages less than 120 Ma, has a mode at ~50 Ma, and a minimum age of 18.2 ± 0.3 Ma. The overlying Miocene Taungtalon Formation and lower Moza Formation have older minimum ages of 29.7 ± 0.6 Ma and 32.9 ± 0.7 Ma, respectively (Fig. 2), and their modal ages are slightly older than that of the Shwetaung Formation. Thus, formations younger than the Shwetaung Formation contain progressively older minimum zircon ages such that the youngest age peaks shifts to being slightly older for younger sedimentary units (Fig. 2). All the Oligocene and Miocene samples contain a small proportion of Jurassic-aged detrital zircons (Fig. 2).

The largest plutonic complex in the Yarlung Tsangpo catchment is the Transhimalayan Gangdese batholith of southern Tibet (Fig. 1) and it has a magmatic history spanning from ~200 Ma to 15 Ma (Ji et al., 2009). The Gangdese and the eastern Transhimalayan batholiths (called Basu-Ramwu, Bomi-Ranwu and Chayu-Shama) of the eastern syntaxis region, the Northern Magmatic Belt of the Lhasa terrane, and the Dianxi Burma batholiths within the Mogok Metamorphic Belt and Slate Belt (Fig. 1) have overlapping magmatic histories (Chu et al., 2006; Liang et al., 2008; Chiu et al., 2009; Mitchell et al., 2012; Xu et al., 2012). The detrital U/Pb ages shown in Fig. 2 are consistent with the Gangdese, eastern Transhimalayan batholiths, or the Dianxi-Burma batholiths and any of these could be the provenance for the Central Myanmar Basin sediments (Fig. 1).

The application of U/Pb and εHf provides a tool for discriminating between batholiths, and we have compiled the published U/Pb and εHf data for the batholiths in the modern day Yarlung Tsangpo, Brahmaputra, and Irrawaddy catchments (Figs. 1, 3) (Bodet and Scharer, 2000; Mo et al., 2005; Chu et al., 2006; Liang et al., 2008; Chiu et al., 2009; Chung et al., 2009; Ji et al., 2009; Mo et al., 2009; Zhu et al., 2009a,b; Zhang et al., 2010; Chu et al., 2011; Guan et al., 2011; Guo et al., 2011; Zhu et al., 2011; Guan et al., 2012; Guo et al., 2012; Ji et al., 2012). The compiled dataset of these published Mesozoic–Cenozoic plutonic sources reflect large variations in εHf from ~−25 to +20 (Fig. 3). Zircons from the Gangdese batholith of the Lhasa terrane in the Yarlung Tsangpo catchment in Tibet have positive (juvenile mantle) εHf values until about 55 Ma (Chu et al., 2011), and younger zircons with U/Pb ages between 55 Ma and 40 Ma have εHf values as low as −7, although most values fall between +5 and +15 (Fig. 3A). A suite of analyses between 35 Ma and 10 Ma have εHf values between +3 to +12. The Northern Magmatic Belt of the northern Lhasa terrane contains Jurassic to Early Cretaceous aged zircons (90–210 Ma) and depleted mantle εHf values of −15 to −5 (Figs. 1; 3A). The Nyingchi metamorphic complex lies directly west of Namche Barwa (Fig. 1) in the southern eastern Lhasa terrane and has very mixed εHf values (−18 to +9) with quite discrete U/Pb ages (Fig. 3A). The eastern Transhimalayan Basu-Ramwu, Bomi-Ranwu and Chayu-Shama batholiths are located within the eastern syntaxis region between the Bangong–Nujiang and Yarlung–Yarlung Tsangpo sutures zones, and the Bomi-Ranwu batholith samples are taken from along the strike of the Jiali Fault (Fig. 1). There are several clusters of zircons ranging from 230 Ma to 40 Ma, and they have depleted mantle εHf values of −20 to −5 (Fig. 3B). The Danxi Burma batholiths, and associated Tengliang and Yingjiang granitoids, represent the intra-Myanmar magmatic arc and lie within the present-day Irrawaddy River catchment (Fig. 1). They form two groups with similar εHf values ranging in age from 100 to 140 Ma and 45 to 80 Ma and have similar values to the Bomi-Ranwu. Data from the Gaoligong granites in Western Yunnan (Xu et al., 2012) are within the eastern Transhimalayan belt and are identical in signature to the Bomi-Ranwu (Figs. 1, 3). U/Pb and εHf values for a Cretaceous jadeite sample in upper Myanmar (Fig. 1) have very high positive εHf values (Fig. 3B). In summary, the published εHf data demonstrate that Gangdese batholith zircons older than 60 Ma and younger than 40 Ma have positive εHf values, and a small portion of Gangdese zircons with ages between 40 and 55 Ma have negative εHf values. Zircons from the Northern Magmatic belt, eastern Transhimalayan batholiths in the syntaxis (Bomi-Basu-Chayu suite), and the intra-Myanmar Dianxi Burma batholiths (and associated granitoids) have negative εHf values (Fig. 3). The U/Pb and εHf signatures of zircons from the above potential source areas can be compared to the detrital zircon signatures of the Eocene to Miocene Central Myanmar Basin sedimentary rocks, in order to determine their provenance and evaluate whether a connection between the Yarlung Tsangpo and Irrawaddy rivers existed during their deposition.

We compare the U/Pb and εHf data for the detrital zircons to these published bedrock datasets, using only zircons less than 300 Ma old (Figs. 3C and 4, Tables S1 and S2) in order to assess if the Eocene to Miocene sedimentary rocks of the Central Myanmar Basin display a provenance signal that is compatible (or not) with the existence of a former Yarlung Tsangpo–Irrawaddy system. The majority of the Late Eocene Pondaung and Middle Oligocene Padaung Formation zircons (89% and 82%, respectively) have εHf values that plot within the Gangdese field (+εHf values between 40 and 120 Ma), and most of the remaining values plot within the eastern Transhimalayan

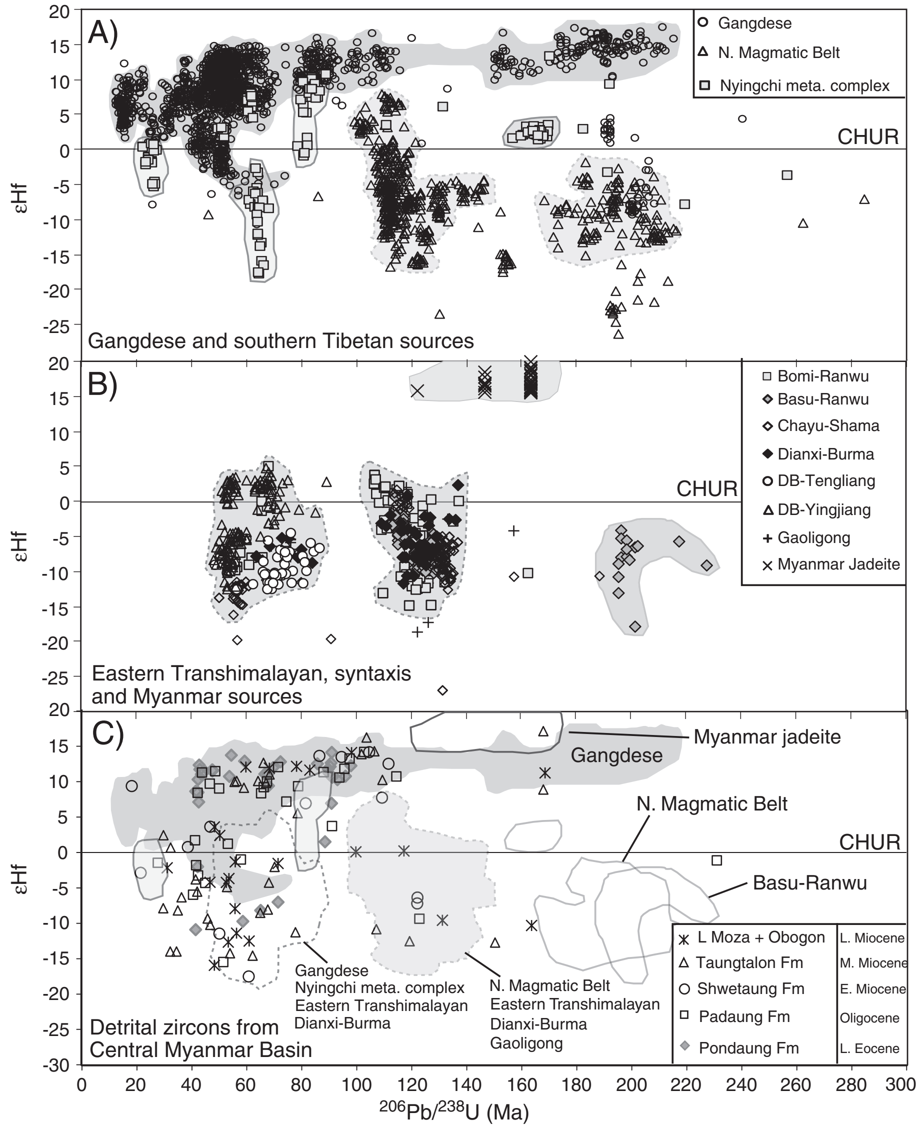

Fig. 3. Comparison of U/Pb and εHf values for published zircon data of bedrock samples (see text for references) and new data for the sedimentary deposits presented in this paper. A. Published data for the Gangdese batholith of Tibet, Northern Magmatic Belt, and Nyingchi metamorphic complex west of Namche Barwe. B. Published data for the eastern Transhimalayan batholiths (the Bomi Ramwu, Basu Ramwu and Chayu Shama), Gaoligong granites, the Dianxi-Burma batholiths within the Mogok Metamorphic Belt and the Slate Belt, and a Myanmar jadeite sample. C. New U/Pb and εHf data for the detrital zircons extracted from the Cenozoic samples from the Central Myanmar Basin. Values representing the batholiths are outlined to highlight potential provenance areas. Sampling locations are shown in Fig. 1. See Tables S1 and S2 for the full tabulated datasets.

(Bomi-Ramwu, Chayu Shama), Nyingchi complex west of Namche Barwa, or Dianzi Burma fields. The youngest detrital zircon (41.4 ± 0.9 Ma) in the stratigraphically lowest Pondaung Formation sample has an εHf value of +8.6 (Table S2). The proportion of Early Miocene Shwetaung Formation detrital zircons plotting within the Gangdese field is 64%, and the youngest zircon (18.2 ± 0.3 Ma) has an εHf value of +9.4; the remaining zircons plot within the Northern Magmatic Belt, eastern Transhimalayan (Bomi-Ramwu, Chayu-Shama) or Dianxi-Burma fields (Figs. 1, 3, 4). The proportion of Middle Miocene Taungtalon Formation zircons plotting within the Gangdese field is 47% and most of the remaining zircons plot outside any of the values covered in the available bedrock εHf datasets. The youngest two zircons are the same age (29.7 ± 0.6 Ma and 29.7 ± 0.7 Ma) and have εHf values of −7.9 and +2.4. Finally, 56% of εHf values for the Middle–Late Miocene lower Moza and Obogon Formations plot within the Gangdese field and most of the remaining zircons plot in eastern Transhimalayan (Bomi-Basu-Chayu) and Dianxi-Burma fields (Figs. 1, 3, 4). The youngest zircon from the Obogon Formation (31.1 ± 0.7 Ma) has an εHf value of −2.2.

4. Interpretation and discussion

We propose that a Yarlung Tsangpo–Irrawaddy connection existed as far back as Late Eocene time (at least 40 Ma), based on our comparison of the available bedrock εHf data and the identification of predominately Gangdese-like sources for the detrital zircons in the Pondaung Formation (Fig. 4). Similarly, the Oligocene deposits are also dominated by zircons with Gangdese-like εHf signatures. In contrast, the proportion of Gangdese-like zircons drops in the Miocene, and the eastern Transhimalayan- and intra-Myanmar Dianxi-Burma-derived zircons increase in the Middle and Late Miocene-aged formations. The youngest detrital zircon in the Early Miocene Shwetaung Formation has a Gangdese-like εHf value. The εHf values for zircons from the Myanmar jadeite of the Wuntho region in the north (Shi et al., 2009) are plotted in

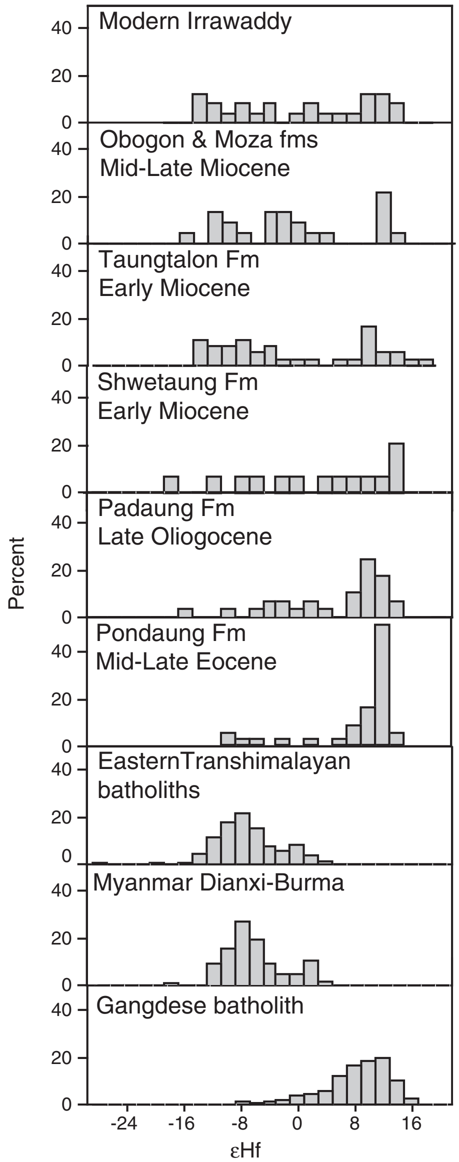

Fig. 4. Comparison of histograms of εHf data for the published bedrock samples (see text for references) and the Eocene to Miocene deposits presented in this study. The modern Irrawaddy data are from Bodet and Scharer (2000). All the published eastern Transhimalayan and Dianxi-Burma analyses combined for simplicity as the U/Pb and εHf for these units are very similar.

Fig. 3. They have positive (+16–+17) εHf values, and are Late Jurassic to Early Cretaceous in age; only one detrital zircon plots within the jadeite belt field (Fig. 3B) and this is from the Miocene Taungtalon Formation. There are volcanic and magmatic events that occurred within the current catchment of the Irrawaddy and Chindwin rivers which span the Jurassic to Miocene timeframe of interest here, for which no εHf values currently exist. However, whole rock Sr–Nd isotopic data have been published with U/Pb ages of zircons for a suite of magmatic rocks in the Shan Scarp and Wunto-Popa arc regions (Mitchell et al., 2012), and the majority (16 out of 19 sets of values) plot within an S-type granite field (εNd values of −5– −12) which would be equivalent to negative εHf values. Three of the nineteen values are I-type (Gangdese-like) granites (εNd values of +3–+12), and of those only one has a U/Pb age that we observe in our detrital zircon age populations. This is the Mokpalin diorite which is located 110 km east of Yangon and has a U/Pb zircon age of 90.8 Ma (Mitchell et al., 2012); it is possible this batholith accounts for a small population of zircons in the Eocene and the Oligocene deposits (Fig. 3C). To the south of Mokpalin lie the granite suites of SW Thailand and southeastern Myanmar, and these have been recently dated by Searle et al. (2012). If Western Burma is restored to its pre-Miocene position by removing between 330 and 1000 km of right lateral offset along the Sagaing Fault (Fig. 1), these regions are potential source areas for the Eocene and Oligocene rocks in the Central Myanmar Basin. However, this province is composed of Triassic I-type and Paleogene S-type granites, and given our detrital age populations and εHf values, neither are large contributors of zircons to the Eocene and Oligocene deposits of the Central Myanmar Basin. We therefore conclude that based on the available bedrock data, the Gangdese batholith is the most likely source for the I-type zircons in the Eocene and Oligocene deposits of the Central Myanmar Basin. In contrast, the increase in the proportion of negative εHf values for detrital zircons in the Miocene deposits reflects an increase in contributions from S-type granites, and therefore the eastern syntaxis, intra-Myanmar Mogok Belt, Shan Scarp, and Wuntho-Popa arc, as well as the Paleogene granites of southeastern Myanmar and SW Thailand, are all potential source areas during the Miocene (Mitchell et al., 2012; Searle et al., 2012).

We consider the change in provenance as a signal of an Early Miocene disconnection between the Yarlung Tsangpo–Irrawaddy and re-routing of Gangdese-derived sediment into the proto-Brahmaputra. Two lines of independent evidence support this interpretation. Firstly, a major increase in sedimentation started in the Bengal Basin in Assam in the Early Miocene with the sediment being derived from the northeast (i.e. the syntaxis) (Alam et al., 2003; Uddin and Lundberg, 2004), and secondly, phylogenic modeling of mitochondrial and nuclear DNA of small freshwater fish in the Yarlung Tsangpo, Irrawaddy and Brahmaputra rivers places species divergence from Yarlung Tsangpo–Irrawaddy clades into Yarlung Tsangpo–Brahmaputra clades at 19–24 Ma (Ruber et al., 2004; Britz, 2009). Our interpretation is consistent with Bengal Fan sediments having a Transhimalayan batholith source for at least the last 12 Ma (Galy et al., 2010). Although Gangdese-derived zircons are present in all the Miocene samples we have studied, and are present in the Miocene samples from the Central Myanmar Basin that Liang et al. (2008) analyzed, we attribute this to Miocene reworking of the Oligocene and Eocene sedimentary successions which are dominated by Gangdese-like zircons.

Cina et al. (2009) present U/Pb and Hf data for detrital zircons from the Upper Miocene Dafla and Subansiri formations near Itanagar in the foothills of the Arunachal Himalaya; the modern Subansiri river is a tributary to the Brahmaputra (Fig. 1). They conclude that the zircons are of Gangdese affinity and are evidence for two river capture events of the Yarlung Tsangpo by the Subansiri (at 10–3 Ma) and Siang (at ~3–4 Ma) rivers. More recently, Chirouze et al. (2013) have demonstrated that the modern Yarlung Tsangpo–Siang–Brahmaputra connection developed around 7 Ma, and that sedimentation in the foothills region of the Arunachal Himalaya is influenced by uplift of the Shillong Plateau 14–8 Ma (Clark and Bilham, 2008) and the potential northwards migration of the Brahmaputra braid plain (Fig. 1). The sections studied by Cina et al. (2009) and Chirouze et al. (2013) are located at the northern edge of the proto-Brahmaputra braid plain which would have extended right across to the Indo-Burman Ranges (Fig. 1). Based on our results, we suggest that the precursor event to the Yarlung Tsangpo–Siang–Brahmatura capture around 7 Ma occurred in the Early Miocene (Yarlung Tsangpo–Lohit–Brahmaputra) associated with the breakdown of the Yarlung Tsangpo–Irrawaddy system, but this requires further testing of the provenance of Oligocene–Miocene age deposits in the depositional center of the proto-Brahmaputra system (Fig. 1).

Allen et al. (2008) noted that the Paleogene sedimentary rocks in the Indo-Burman Ranges contain significant arc-derived detritus. They considered that source to be derived from the east (in Myanmar), rather than the north or west (i.e. a Transhimalayan source transported by the Brahmaputra), because of the paleogeographic constraints imposed by Oligocene sedimentary sequences in the Bengal Basin which lack Transhimalayan-sourced material. Based on our U/Pb and εHf data and interpretations for the Paleogene deposits of the Central Myanmar Basin, we consider that the requirement for an eastern source area for the Paleogene deposits of the Indo-Burman Ranges is readily satisfied with a Yarlung Tsangpo–Irrawaddy River transporting Gangdese detritus through the Western and Eastern Troughs to the Indo-Burman Ranges depocenter. New εHf data for the detrital zircons of the Paleogene sequences of the Indo-Burman Ranges could provide a further test of this hypothesis. The Neogene deposits of the Indo-Burman Ranges have most affinity to the Himalayan foreland basin deposits (Allen et al., 2008), and therefore, both the Indo-Burman Ranges and the Central Myanmar Basin show provenance shifts between the Paleogene and Neogene. A possible mechanism that explains the shifts observed in both the Indo-Burman Ranges and the Central Myanmar Basin is that the Yarlung Tsangpo–Irrawaddy river fed sediment into the Central Myanmar Basin and the Indo-Burman Ranges in the Middle–Late Eocene and Oligocene, until uplift, extension and normal faulting in the Central Myanmar Basin and deformation in the early Miocene (Pivnik et al., 1998; Bertrand and Rangin, 2003) caused compartmentalization of the Central Myanmar Basin from the Indo-Burman Ranges. The connectivity between the Paleogene systems of the Central Myanmar Basin and Indo-Burman Ranges is in agreement with Chhibber (1934) and Mitchell (1993), who considered the Paleogene Indo-Burman Ranges to be an extension of the Western Trough forearc sediments.

4.1. Discussion

We link the breakdown of the Irrawaddy–Yarlung Tsangpo river system primarily to tectonic forcing for the following reasons. Diachronous cooling occurs in the Mogok Metamorphic Belt (Mogok Metamorphic Belt) from ~30 Ma in the south of Myanmar to 18 Ma in the syntaxis region (Bertrand et al., 2001), following high grade metamorphism from 49 to 29 Ma (Searle et al., 2007). By the Early Miocene, there is evidence for exhumation in the syntaxis (Booth et al., 2004) and onset of right-lateral movement on the Jiali–Parlung, Gaoligong and Sagaing faults (Gilley et al., 2003; Gururajan and Choudhuri, 2003; Booth et al., 2004; Lin et al., 2009), as well as extension in the Central Myanmar Basin (Pivnik et al., 1998; Bertrand and Rangin, 2003) (Fig. 1). The onset of deformation along the Jiali–Parlung shear zone is significant as it is the most likely location for the Yarlung Tsangpo–Irrawaddy River (Fig. 1). An Early Miocene age of river re-organization in the eastern syntaxis is coincident with the final stages of southeast extrusion of the Burma block (Leloup et al., 2001; Replumaz et al., 2010) and a period of widespread leucogranite genesis and exhumation in the Himalayan orogen (Harrison et al., 1992; Harris, 2007; Searle et al., 2010). Further east, the establishment of the modern route of the Yangtze River has recently been constrained to be sometime before 23 Ma, and younger than Eocene time (Zheng et al., 2013), and reflects slightly earlier river re-organization associated with uplift of the Tibetan Plateau and strike-slip motion along the Red River Fault zone. There is growing evidence that the Asian monsoon intensified in the Early Miocene (Clift et al., 2004, 2008; Wan et al., 2010) and therefore elevated rainfall could have influenced headward erosion and river capture by the proto-Brahmaputra and its tributaries.

We propose that the breakdown of the Yarlung Tsangpo–Irrawaddy river occurred in the Early Miocene, and since the depositional age of the Miocene sedimentary rocks is not well constrained, we tentatively place the timing of the event to around 18 Ma based on the age of the youngest zircon in the dataset (the Shwetaung Formation) which also has a Gangdese provenance. The age of the youngest zircons in the Middle–Late Miocene deposits becomes progressively older, reflecting exhumation and recycling of older sedimentary units and source terrains in the syntaxis and upper Myanmar. We propose that the early collisional (Eocene) phase of the Himalayan orogeny involved erosion by an orogen-parallel river system which transported sediment along the Indus–Yarlung Tsangpo suture zone (and onto the West Burma block) as India collided with Asia. When the post-Miocene strike slip offset along the Sagaing Fault is restored (Mitchell, 1993), the river system draining southern Tibet would have been comprised of the modern Yarlung Tsangpo, Irrawaddy and Chindwin rivers (Figs. 1, 5). The Yarlung Tsangpo–Irrawaddy–Chindwin river system continued to be connected through the Oligocene. Our data demonstrate that, by Early Miocene time, provenance changed and the Gaoligong and intra-Myanmar Dianxi-Burma batholiths, and potentially other S-type batholiths along the western section of the Sibumasu block (Figs. 1, 5), became the dominant provenance areas for the Central Myanmar Basin, and older sedimentary units within the basin were recycled. We propose that exhumation and deformation along the Jiali–Parlung and Gaoligong shear zones (and associated headward erosion by a tributary of the paleo-Brahmaputra) and along the Mogok Metamorphic Belt caused the Yarlung Tsangpo–Irrawaddy connection to fail and provenance areas to change. An approximate 18 Ma timing for the establishment of the paleo-Brahmaputra provides a constraint on the length of time required to develop the modern day Yarlung Tsangpo–Brahmaputra, thought to be in its current position by 7 Ma (Chirouze et al. (2013)).

The results from molecular phylogenetic modeling of *Badidae* freshwater fish found in the modern Yarlung Tsangpo–Brahmaputra, Ganges and Upper Irrawaddy rivers suggest an Eocene origin for the family, and the divergence of two species into Irrawaddy and Yarlung Tsangpo–Brahmaputra clades occurred around the Oligocene–Miocene boundary (Ruber et al., 2004). Our data allows us to refine this species divergence to around 18 Ma, and to provide further evidence for the coupling between tectonic and surface processes, and how these affect the evolution of fish species. Finally, there are other biological evolution implications arising from our results. Myanmar has a rich fossil mammal inventory chiefly from the Middle Eocene Pondaung Formation. Intriguingly, the establishment of a Yarlung Tsangpo–Irrawaddy–Chindwin river corridor opens up the possibility that this route was used in the earliest anthropoid radiation, alongside the migration of primitive wolves (*Proviverrine hyaenodontids*), from Africa and Europe into SE Asia. Cladistic analysis of a species of *Proviverrine* found in the Pondaung Formation, and also in Europe, Pakistan, and Africa, suggests that it originated in Europe in the early Eocene and dispersed into southeast Asia by Late Middle Eocene time (Egi et al., 2005).

5. Conclusions

Our U/Pb and εHf data demonstrate that zircons which originated in the Gangdese batholith in Tibet are contained in the Middle–Late Eocene sedimentary rocks of central Myanmar. It is possible that one of the longest records of erosion of the eastern Himalayas is stored in the Central Myanmar basin, which may be of similar duration to the Indus Fan sedimentary rocks that record erosion of Transhimalayan rocks in the Middle Eocene (Clift et al., 2001). We have determined that a major orogen-parallel river system, the Yarlung Tsangpo–Irrawaddy, drained the Indus–Yarlung Tsangpo suture zone as an antecedent river system during the early stages of the Himalayan orogeny. When the post-Miocene strike-slip offset along the Sagaing Fault is restored (Mitchell, 1993), the river system draining southern Tibet would have been comprised of the modern Yarlung Tsangpo, Irrawaddy and Chindwin rivers (Figs. 1, 5). Our geochronology constrains the timing of major reorganization of rivers in the eastern syntaxis, and we suggest that this reorganization was a response to the northward migration of uplift and exhumation in Myanmar and increased deformation in the eastern syntaxis. We postulate that the earliest Yarlung Tsangpo–Brahmaputra linkage around 18 Ma was through the Lohit River and that a succession of anti-clockwise capture events (Lohit, Dibang, Siang) followed, reflecting the final northward migration of uplift and deformation in the syntaxis (Figs. 1, 5).

Our paleogeographic reconstruction emphasizes the role that strike-parallel (longitudinal) rivers play in the early life of orogens

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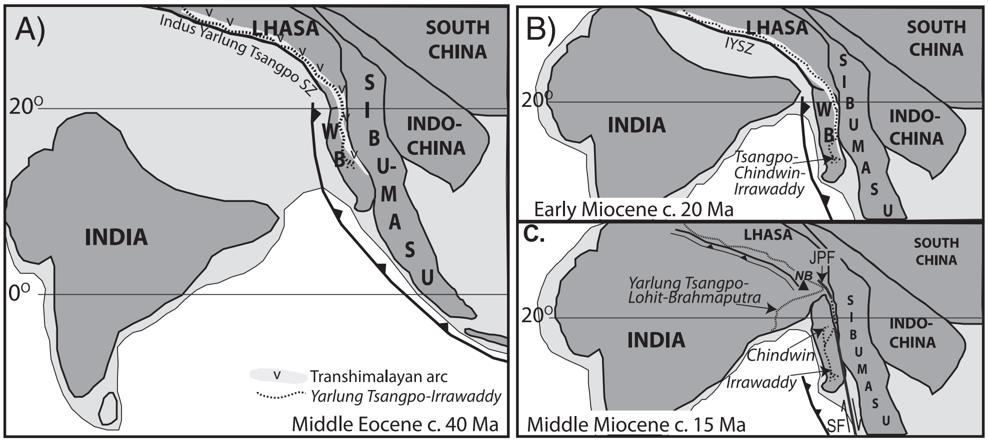

Fig. 5. Paleogeographic reconstruction. A. Schematic reconstruction of rivers and suture zones for Late Eocene time (c. 40 Ma). Note the major rivers, including the Tsangpo–Irrawaddy system, run parallel to the orogen. The continuous Transhimalayan arc includes the Gangdese batholith, eastern Transhimalayan batholiths and the Mogok Metamorphic Belt and Slate Belt of Myanmar. B. During Early Miocene time (c. 20 Ma), the Tsangpo–Irrawaddy river keeps pace with deformation around the syntaxis. C. By the Middle Miocene (c. 15 Ma), the Yarlung Tsangpo–Irrawaddy river has disconnected, and the Yarlung Tsangpo has been captured by the Lohit River (a tributary of the modern Brahmaputra). Namche Barwe is only shown to locate position of the syntaxis. Tectonic reconstructions and position of the West Burma block relative to the Lhasa terrane and SE Asia are based on Hall (2002) and Metcalfe (2011).

and in the evolution of sedimentary systems and landscapes during orogenesis. The modern Mekong, Salween and Yarlung Tsangpo rivers are antecedent on major suture zones (Fig. 1) and the pre-Himalayan collision between Asia and the Songpan Ganze and Qiangtang terranes is recorded in the detrital sediments of the modern Red, Mekong and Salween (Bodet and Scharer, 2000; Clift et al., 2006; Hoang et al., 2009). The Eocene sedimentary rocks in central Myanmar contain a record of the early phases of the Himalayan orogeny, and notably, this early detritus is not found in the foreland basin. For the Himalayan orogeny, the Eocene–Oligocene sedimentary molasse is deposited in basins originally aligned parallel to the strike of the orogen.

Finally, we are able to address key questions about the evolution of some of the great Himalayan river systems and the timing of river capture events. Our data supports the Yarlung Tsangpo–Irrawaddy linkage proposed by Burrard and Hayden (1907), Seeber and Gornitz (1983), Brookfield (1998) and Clark et al. (2004), and demonstrates that the Yarlung Tsangpo–Irrawaddy system existed as far back as 40 Ma (and possibly longer). Clark et al. (2004) proposed that the Yarlung Tsangpo was originally connected to the Red River, but we have demonstrated that it is very unlikely that the Yarlung Tsangpo was ever connected to the Red River, which supports the findings of Hoang et al. (2009), or the Salween. The major river diversion that provides the linkage between Transhimalayan rocks, the foreland basin and the Bengal Fan, and sets up the precursor drainage system to the modern Tsangpo–Siang–Brahmaputra, occurred around 18 Ma.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2013.07.002.

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