A palaeo Tibet–Myanmar connection? Reconstructing the Late Eocene drainage system of central Myanmar using a multi-proxy approach

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Abstract: Strain resulting from the collision of India with Asia has caused fundamental changes to Asian drainage patterns, but the timing and nature of these changes are poorly understood. One frequently proposed hypothesis involves the connection of the palaeo Tsango drainage to a precursor to the Irrawaddy River of central Myanmar in the Palaeogene. To test this hypothesis, we studied the provenance of Palaeogene fluvio-deltaic sedimentary rocks that crop out in central Myanmar, namely the Late Middle Eocene–Early Oligocene Pondaung and Yaw Formations. Isotopic analysis on bulk-rock and petrographic data indicate a primary magmatic arc source, and a secondary source composed of recycled, metamorphosed basement material. Although the exact location of both sources is hardly distinguishable because Burmese and Tibetan provinces share common lithological features, the presence of low-grade metamorphic fragments, the heterogeneity in Sr–Nd isotopic values of bulk sediments and westward-directed palaeo-flow orientations indicate a proximal source area located on the eastern Asian margin. Central Myanmar was the locus of westward-prograding deltas opening into the Indian Ocean, supplied by the unroofing of an Andean-type cordillera that extended along the Burmese margin. We found no evidence to support a palaeo Tsango–Irrawaddy River, at least during the Late Eocene.

Supplementary material: Data locations, and isotopic and petrographic results are available at www.geolsoc.org.uk/SUP18655.

The major East Asian rivers have elongated and irregularly shaped drainage basins that have been explained as the consequence of drainage reorganization associated with uplift of eastern Tibet, most probably in the Miocene (Brookfield 1998; Clark et al. 2004, Clift et al. 2008). The unique geometry of the Tsango River, with its abrupt and tight loop in the deeply incised gorges of the Namche Barwa massif, and the close proximity of several major rivers in the eastern Himalayan syntaxis region suggest that drainage patterns in the past were very different (see Fig. 1a; Brookfield 1998). These changed when the region was subjected to rapid uplift and erosion that caused a series of drainage reversal and capture events (Clark et al. 2004). One of the most popular models proposes a previous connection between the Yarlung–Tsango and the nearby Irrawaddy River via the Parlung and Lohit Rivers (Fig. 1a; Stamp 1940). However, this commonly held hypothesis has not been extensively studied, and little attempt has been made to better constrain the timing of the proposed Irrawaddy–Tsango diversion. Nevertheless, recent work based on phylogenetic studies of freshwater fish has suggested that if any connection existed it would have ceased by the Early Miocene (Ruber et al. 2004).

The Central Myanmar Basin contains an almost continuous succession of Cenozoic sedimentary rocks most of which are associated with fluvio-deltaic depositional environments (see Fig. 1c). During the Palaeogene, rates of deposition were high (Metivier et al. 1999), and the large thicknesses of the Late Middle Eocene to Early Oligocene Pondaung and Yaw Formations represent a significant proportion of the Palaeogene sediments deposited in central Myanmar (United Nations 1978). Rocks of this age are good candidates for a provenance study to test whether palaeo-rivers of Myanmar were once connected to Tibet.

To define the sediment provenance, this study adopted a multi-proxy approach, combining sedimentological, petrographic, and isotopic analysis. Rocks of Asian and Indian affinity are distinct in terms of their isotopic, geochemical and petrographic characteristics (DeCelles et al. 2001; Kapp et al. 2003; Chung et al. 2005). Because the Yarlung–Tsango River flows through the region of the Indus–Tsango Suture Zone, the boundary between Indian and Asian crust, any previous connection to the Irrawaddy would be reflected by the presence of sediments with features diagnostic of these regions (i.e. Transhimalayan material), thus provenance studies may be used to reconstruct palaeo sediment routing systems. Tools for tracing provenance are numerous, and have been widely used to help reconstruct the evolution of the Indo-Asian collision (see, e.g. Najman 2006, for a comprehensive review). Methods used include palaeocurrent analysis, quartz–feldspar–lithic fragment (QFL) point-counting, heavy mineral identification, and Nd and Sr isotopic analysis of bulk sediments (France-Lanord et al. 1993; Uddin & Lundberg 1998a; Colin et al. 1999; Pierson-Wickmann et al. 2001; Clift et al. 2001, 2006; Najman et al. 2008).
Geological and palaeogeographical framework

Central Myanmar constitutes the southeastern end of the eastern Himalayan syntaxis, which forms a complex pattern of continental blocks that accreted to Asia throughout the Palaeozoic and Mesozoic (Metcalfe 1991). The Burma terrane forms the bulk of central Myanmar and is at present overlain by the Central Myanmar Basin (Fig. 1b). The Burma terrane collided with Asia during the Cretaceous period, and forms the southeastward neighbour of the Lhasa terrane, which occupies the southern part of the Tibetan Plateau and which collided with Asia during the Late Jurassic–Early Cretaceous (Mitchell 1993). The Shan–Thai Plateau forms a large and elevated area in eastern Myanmar, and constitutes a local unit of the Sibumasu block (Bender 1983; Searle et al. 2012). At the transition between the Central Myanmar Basin and the Shan–Thai block, the deep basement of the Burma terrane is partially exhumed and comprises a succession of metamorphic belts (Bertrand & Rangin...
Until the Middle Miocene, the Indo-Burman Ranges were separated from the Assam Basin by the Indo-Burman Ranges, which constitute the Cenozoic accretionary complex. The presence of the Indo-Burman Ranges during the Eocene is not documented. CMB, Central Myanmar Basin; TSS, Tethyan Sedimentary Series.

On its western margin, the Central Myanmar Basin is separated from the Assam Basin by the Indo-Burman Ranges, which constitute the Cenozoic accretionary complex produced by subduction of the Indian Plate under the Burma terrane. Central Myanmar Basin; TSS, Tethyan Sedimentary Series.

Following the Cenozoic deformation of Asia in response to India’s penetration, central Myanmar primarily followed the northward motion of the Indian Plate and the rotational motion of the Indochina Plate, through intense strike-slip deformation and c. 20–30° clockwise rotation relative to South China. The presence of the Indo-Burman Ranges during the Eocene is not documented. CMB, Central Myanmar Basin; TSS, Tethyan Sedimentary Series.

The palaeogeographical reconstructions of Hall (2002) and Morley (2002, 2004, 2009) summarize and represent a compromise between the various palaeogeographical models. Late Middle Eocene simplified palaeogeography of the region is shown in Figure 2a, and a schematic structural map of central Tibet and Myanmar is proposed in Figure 2b. In the Eocene collision zone, central Tibet constitutes an area of old, inherited and young, collision-related highlands (Rowley & Currie 2006;Dupont-Nivet et al. 2008; Wang et al. 2008). North of the Indus–Tsangpo Suture Zone, the Asian basement is composed of granitic and sedimentary terrains of the Lhasa terrane (Kapp et al. 2003). The Transhimalayan arc represents the original Andean-type continental arc, formed by the subduction of Tethyan oceanic crust beneath the Asian active margin (Chung et al. 2005; Ji et al. 2009). In Eocene times, the Tibetan Sedimentary Series, a Palaeozoic to Eocene sedimentary succession deposited on the northern passive margin of India, may have been uplifted early and exposed south of the Indus–Tsangpo Suture Zone (Najman 2006; Najman et al. 2008). Further east, the Burmese margin was occupied by the Burmese magmatic arc, considered as the eastward continuation of the Transhimalayan arc and today represented by isolated granitoid exposures in the Burma basement terrane (Zaw 1990; Mitchell 1993; Mitchell et al. 2012). Further inland, the Shan and Yunnan highlands have been emergent since the Late Cretaceous period (Bender 1983), and have undergone minor uplift during the Palaeogene (Morley 2004). The Central Myanmar Basin constituted a NW–SE-oriented ribbon of pull-apart sub-basins, situated in a typical fore-arc position between the Burmese magmatic arc and the Indo-Burmese trench, where the Indo-Burmese rise is currently located.

The time at which the Central Myanmar Basin became isolated from the proto-Bengal fan and the Assam Basin on its western margin by the uplift of the Indo-Burman Ranges remains unknown. Maurin & Rangin (2009) demonstrated a Late Miocene uplift of the ranges, but the Central Myanmar Basin has been enclosed since at least the Middle Miocene, as it has been the locus of north–south prograding deltaic formations, recorded in the Pegu Group series (Khin & Myittha 1999). Poorly dated Eocene flysch-type sediments extend over the entire length of the inner wedge of the ranges, from the Arakan Yoma (southern edge of the ranges) to the Naga Hills (northern edge of the ranges; see Brunnsschweiler 1966; Bannert et al. 2011), and indicate that the Indo-Burman Ranges were not emergent in the Middle Palaeogene. A combined petrographic and isotopic study of flysch sandstone samples from the Arakan Yoma identified a significant component of arc-derived material coming from the Asian active margin, and a persistent youngest zircon fission-track population at 37 Ma in the sandstones (Allen et al. 2008). Therefore, the Indo-Burman Ranges must have experienced a first uplift episode sometime between 37 Ma (Late Middle Eocene) and the Middle Miocene (Mitchell 1993; Allen et al. 2008).

In the Minbu and Chindwin Sub-Basins, the locations of the present study, the Pondaung and Yaw Formations represent a significant proportion of the Palaeogene deposits that are locally up to 2000 m in thickness (United Nations 1978). The Pondaung Formation contains...
Late Middle Eocene continental fauna, and fluvo-deltaic deposits constitute the main outcrops (Jaeger et al. 1999; Beard et al. 2009), characterized by a high density of palaeosols: the ‘cherry-red, bright buff and cream-white earths’ already observed by Pilgrim & Cotter (1916). Lateral variations in facies are common, and fine-grained floodplain sediments alternate with pond-like deposits, crevasse splayds and channel bodies (Soe et al. 2002). The magnetostratigraphic study of Benammi et al. (2002) of the upper part of the formation yielded a constant normal polarity throughout 319 m of deposits, indicating that this decametre-thick series would have been deposited in less than 1 Ma (maximum length of Bartonian polar chron periods potentially contemporaneous with these deposits; Benammi et al. 2002), owing to a high accumulation rate (>0.3 mm a⁻¹). The Yaw Formation is the marine successor of the Pondaung Formation, and has been far less studied until now. In the Chindwin Sub-Basin, the Yaw Formation is especially thick and yielded Late Eocene to Early Oligocene foraminifera (Nagappa 1959).

Sampling sites and analytical methods
During the 2011 and 2012 winter seasons, we explored, described and sampled several Eocene exposure sites in both the Minbu and Chindwin Sub-Basins, paying special attention to the continental Pondaung and marine Yaw Formations. In the Minbu Sub-Basin, 11 sites were explored in the fossiliferous area of the Bahin township (site A, Fig. 1a); In the Chindwin Sub-Basin, most of the visited outcrops are situated in Kalewa township, along the Kalewa–Kalaymyo road (site B, Fig. 1a), where the Yaw Formation is especially exposed. All of the studied sites are both the western margin of the Central Myanmar Basin, close to its boundary with the Indo-Burman Ranges (Fig. 1), and have been exhumed and exposed with a slight dip angle by successive Miocene-Pliocene inversion episodes (Pivnik et al. 1998). Sites were logged, described and photographed; palaeoflow directions were measured on sandstone trough cross-bedding on 3D outcrops, according to standard field methods (Collinson & Thompson 1989).

Sandstone and mudstone samples of both the Yaw and Pondaung Formations, sampled in a 25 km wide area in Bahin township (site A, Fig. 1a), were selected to represent all of the various observed facies. To determine their contents in quartz, feldspar and lithic grains, five sandstone samples were selected and mounted in a synthetic resin from which thin sections were prepared at the Hydras laboratory (Poitiers), whereas larger bodies form multi-storey stacked sandstone successions. Each sand body displays a characteristic inverse-grading, with coarse and erosive basal layers of low-angle planar stratifications, overlain by several tabular sets (20–80 cm thick) of trough cross-stratification, which are the dominant facies of the sandstone bodies. Basal lags of pebbles and cobbles are common. Among the clasts, volcanic rocks, composed of olivine and pyroxene-rich volcanic conglomerates, basaltic, trachytes and rhyolites were notably recognized. Palaeoflow measurements on trough cross-bedding show an unequivocal unimodal westward direction before any rotational correction (see Fig. 3a). The array of measured directions extends from the NW to the SSW.

In the Minbu Sub-Basin, the Yaw Formation is poorly exposed. Outcrops in the Bahin area (area A in Fig. 1a) display horizontally laminated mudstones with sparse millimetre-scale silty and wavy laminates, and rare centimetre-thick carbonate layers. These deposits yielded several shark teeth and shellfish fragments; ichnotaxa are rare, but Thalassinoides and Planolites have been locally recognized; metre-thick tempestite sandy sets have also been observed and yielded shellfish and fossil wood fragments. In the Chindwin Sub-Basin, the Yaw Formation is far better exposed in the Kalewa township (area B in Fig. 1a), and thick outcrops, exposed during excavation for coal mining, could be logged (see Fig. 3b). The Yaw Formation comprises a succession of coarsening-upward, 10–30 m thick sequences. Basal deposits of the type-sequence are composed of grey to black laminated mudstones with a high content of organic matter (facies Fo), interrupted by decimetre-thick, laterally continuous carbonated layers (micritic
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Organic matter content:–M

ichnotaxa, fresh- Roselia thick), with flaser bedding with organic matter and lignite drapes (Kalewa road, 23°09'17.2"N, 94°14'59.0"E). OM, organic matter.

Sedimentary log of an isolated coal mine, Yaw Formation, showing a standard coarsening-upward sequence overlain by stacked sets of trough cross-stratification (60–100 cm thick). Sedimentary structures: (facies St)

\[\text{Carbonate layer (facies Cw)}\]

\[\text{Trough cross-bedding (facies St)}\]

\[\text{Planar stratifications (facies Fo)}\]

\[\text{Ripples (facies Sp)}\]

\[\text{Leaf fragments} \]

\[\text{Fossil bones} \]

\[\text{Molluscan shells} \]

\[\text{Cruziana ichnofacies} \]

Palaecurrents

\[\text{Pondaung Formation} \]

\[\text{(facies St of Soe et al. 2002)}\]

\[\text{Yaw Formation} \]

\[\text{(facies St)}\]

Fig. 3. (a) Measured palaecurrents in sandstones bodies of both Pondaung and Yaw Formations. (b) Sedimentary log of an isolated coal mine, Yaw Formation, showing a standard coarsening-upward sequence (Kalewa road, 23°09'17.2"N, 94°14'59.0"E). OM, organic matter.

wackestone, facies Cw). These mudstones are 2–15 cm thick and are overlain by a coarsening-upward succession of small 3D ripples (2–3 cm) with organic matter laminae as drapes (facies Sp) and centimetre-thick sets of wavy stratifications (facies Sw). Set surfaces of both facies are extremely rich in plant debris; the sets can contain flasers of pure organic matter, and can be interrupted by several centimetres of fine grained, and sandstones can be micaceous. Palaeocurrent analysis on trough cross-bedding (facies St) of Soe et al. (2002) shows similar patterns to the Pondaung Formation, with unimodal, west-directed results, from NW to SW, before any rotational correction (see Fig. 3a).

Petrographic data

QFL and lithic grain plots of the point-counting results are presented in Figure 4. All samples show a significant proportion of volcanic lithics and plot in the magmatic area province on the QFL plot of Dickinson (1985). Volcanic lithic grains are dominant, whereas sedimentary and metamorphic lithic grains are less common, and are found in similar proportions. The Metamorphic Index of Garzanti & Vezzoli (2003) shows very low values, between 100 and 150 (on a scale varying from 100 to 500).

Heavy mineral fractions show a strongly depleted assemblage (see Table 1); in other words they display very low contents of transparent heavy minerals and a scarcity of pyroxene and amphibole, indicating extensive diagenetic dissolution. Opaque phases (rutile, ilmenite, Cr-spinel) represent a significant proportion of the observed grains (from 17 to 45%). Epidote, ilmenite and rutile are the most frequently detected minerals, with minor amounts of Cr-spinel, alkali amphibole (glaucochane), clinopyroxene, tourmaline and anatase. Titanite, pumppellyite, hornblende and chlorite were occasionally detected. We note the lack of zircon in the ultra-stable phase.

XRD analyses of <2 μm fractions of six samples show a prominent contribution of smectite with subordinate amounts of kaolinite and illite. Chlorite has also been detected in the analysed sample of the Yaw Formation, as well as smectite–illite mixed layer clays in one pedogenized sample of the Pondaung Formation.

Nd and Sr isotopic results

Results for both the Yaw and Pondaung Formations are plotted in Figure 5a. Pondaung isotopic results show an unusually wide range, from +0.3 to −7.8 for εNd (with an average of −4.3) and from 0.705 to 0.718 for \(87^\text{Sr}/86^\text{Sr}\) (with an average of 0.7119). Among these results, two distinct families can be distinguished: sediments from the Paukkaung, Nyuangpinle and Pangan localities yielded very high εNd (+0.3 to −3.8) and low to moderate \(87^\text{Sr}/86^\text{Sr}\) ratios (0.705–0.711) and constitute one source family; sediments from the Yarshe, Thaminchauk and Ganle localities yielded substantially lower εNd (−3.9 to −7.8) and higher \(87^\text{Sr}/86^\text{Sr}\) ratios (>0.714), and form a second family. Neither family displays a stratigraphic trend or any geographical zonation (see Fig. 5b and c). The <2 μm and >63 μm fractions of the same samples show significant differences in εNd (up to four) and \(87^\text{Sr}/86^\text{Sr}\) (up to 0.003), but stay within the range of values of the corresponding family.

Yaw isotopic results also display a wide range of values, with εNd from −2.5 to −7.5 (with an average of −5.3) and \(87^\text{Sr}/86^\text{Sr}\) from 0.708 to 0.714 (with an average of 0.7115). Nevertheless, these results form a unique group, which occupies the space between the two Pondaung families on the εNd v. \(87^\text{Sr}/86^\text{Sr}\) diagram. We note that three εNd measurements on Palaeogene flysch of the Indo-Burman Ranges yielded similar values (between −4 and −7.4; see Allen et al. 2008).

Interpretation

Sedimentological interpretation and depositional patterns

Wing-shaped sandstone bodies of the Pondaung Formation display a standard fining-upward sequence dominated by trough cross-beds; their sedimentary profile and their characteristic wing shape clearly evoke channel bodies (Gibling 2006). Soe et al. (2002)
interpreted the Pondaung Formation as representing a fluvio-deltaic environment, where crevasse splay, swale-fill, overbank, fluvial and distributary channel, marsh and prodelta deposits were identified. The coarsening-upward sequences of the Yaw Formation, with their gradual transition from laminated mudstones to cross-laminated ripples with shallow marine ichnofauna, sandstone bodies and continental fossil-bearing coal, show a continuous shift from shallow marine to continental facies. They are interpreted as deltaic deposits, with successive shifts from the distal prodelta (facies Fo/Sw), to the delta front (facies Sp, Sw and Cs), and finally to the delta plain, with distributary channel deposits (facies St) and swamp coals (facies Cv; see, e.g. Styan & Bustin 1984; Postma 1990).

The depositional environments of the Pondaung and Yaw Formations display a gradual shift from onshore fluvial or deltaic deposits to purely deltaic deposits, and reflect an overall transgression, which could be caused either by increased subsidence or by eustatic variations. In the present-day reference frame, mean channel palaeoflow directions of both formations are unimodal and (westward-) directed towards the Indo-Burman Ranges (see Fig. 1). These results show that during the time of interest the Central Myanmar Basin was not topographically enclosed on its western border, as deltaic formations prograded through its western margin, and that the Indo-Burman Ranges were not emerged. This provides a younger time constraint on the early emergence of the Indo-Burman Ranges than previous estimates (post 37 Ma, Allen et al. 2008), and shows that central Myanmar was open to the Indian Ocean until at least Early Oligocene times. Taking into account a 20–30° clockwise rotation for Indochina since the Eocene, and assuming the absence of significant rotation between the Burma block and Indochina, these deltas would have been SW-directed in an Eocene geographical reference frame (Richter & Fuller 1996; Benhammi et al. 2002; Morley 2009). The palaeo-shoreline drawn by these deltas would have been oriented NW–SE, corresponding to the general Eocene orientation of Indochina (see Fig. 2a). These observations suggest that regardless of the extent of strike-slip motion of the Burma block along Indochina since the Eocene, Pondaung–Yaw upstream river systems had to flow through the eastern margin of the Burma block.

**Provenance significance of petrographic observations**

Point-counting analysis of sandstone samples yielded fairly uniform results, with similar QFL percentages and lithic contents. All sandstone samples plot within the magmatic arc provenance on the QFL plot. A sample of Palaeogene flysch from the Indo-Burman Ranges analysed by Allen et al. (2008) plots close to the sandstone samples on the QFL plot, but is more enriched in volcanic lithic material.

Heavy mineral fractions are highly depleted in the more alterable fractions and must be interpreted with caution. The presence of epidote, glaucophane and pumpellylite suggests a low-grade metamorphic source contribution (Mange & Maurer 1992). The high abundance of Cr-spinel may indicate an ultramafic source, which could have been partially removed during later sample dissolution. Concerning the clays, high smectite content in the mudstones suggests a mafic character for the drained area, as smectite commonly results from the weathering of basic substratum (Wilson 2004).

Interestingly, the combination of recycled sediments, low-grade metamorphic rocks and hypothetical ultramafic detritus is common in foreland basins associated with Andean-type margins, and constitutes an ‘axial belt source’ resulting from the erosion of the local basement (Garzanti et al. 2007). Based on our different petrographic approaches, two main sources can be distinguished, which are consistent with the standard description of common orogenic sediment provinces of Garzanti et al. (2007): a ‘magmatic arc source’, which contributed to the numerous volcanic lithic clasts, and an ‘axial belt source’, contributing metamorphic and sedimentary lithic clasts and low-grade metamorphic and probable ultramafic heavy minerals.

**Explaining the dual isotopic signal of the Pondaung Formation**

Two distinct isotopic source contributions can be distinguished for the Pondaung Formation. The supply of the Pondaung river system appears to be heterogeneous and shifts from one source to the other, both geographically (Fig. 5b) and stratigraphically (on decametre-scale, see Fig. 5c). At least three stratigraphic shifts in sourcing would have occurred in less than 50 ka, according to the estimated sedimentation rate of the Pondaung Formation (Benhammi et al. 2002). The high isotopic variability of the deposits in the Pondaung palaeo-floodplain points to a rapidly evolving river system with an unbuffered, heterogeneous load.

Yaw marine sediments are more homogeneous, and possess isotopic ratios that are situated exactly between the two identified source contributions of the Pondaung river system. The similarity of the mean isotopic ratios and the homogeneous petrographic results of the two formations suggest that Yaw and Pondaung Formations were fed by the same sources. At least two distinct sources were isotopically identified, but the two formations reflect different extents of homogenization of material from these sources. Whereas the Pondaung deposits retain the distinct isotopic signatures of these
two provinces and thus reflect inefficient mixing, the Yaw deposits display a relatively well-mixed signal of the two sources. The differences in the isotopic patterns of the two formations can be easily explained by their respective continental and marine characters. The Pondaung and Yaw Formations can be seen respectively as the onshore and offshore parts of the same unbuffered deltaic system, which was supplied by an isotopically heterogeneous drainage basin. Onshore Pondaung deposits, which were located landward, represent the successive ephemeral contributions of distinct areas of the drainage basin, whereas marine or deltaic Yaw deposits, located seaward of the coast, reflect efficient mixing of approximately equal contributions from the two sources, producing a smoothed and fairly homogeneous isotopic signal. As the Yaw Formation overlies the Pondaung deposits without unconformity, the changing degree of isotopic homogenization reflects a transgression-related shift towards marine conditions favouring more efficient mixing. The heterogeneous mixing in the Pondaung deposits is inconsistent with a long-distance, stable sediment supply from two distal catchment areas, as extensive transport would tend to homogenize the isotopic signal along the river course (e.g. Singh & France-Lanord 2002). These results suggest a fast-evolving river system with local catchments, rather than a long transport distance for the Pondaung–Yaw deposits.

**Identification of the provenance areas**

In the direct vicinity of the SE Asian margin, five main geological provinces are believed to contribute to the Eocene Burmese supply: the Transhimalayan magmatic arc, the Lhasa terrane and the Tethyan Sedimentary Series in central Tibet, the Burmese magmatic arc and the Burma terrane in Myanmar (see Table 2).

In central Tibet, the northern part of the Lhasa terrane is dominated by Palaeozoic to Mesozoic sedimentary rocks intruded by S-type granitic batholiths of the Northern Plutonic Belt (Kapp et al. 2003; Chiu et al. 2009). At the southern margin of the Lhasa terrane, the Transhimalayan arc area is dominated by Andean-type volcano-plutonic intrusions (the Gangdese batholith) and ophiolite emplacement at the Indus–Tsangpo suture (Chung et al. 2005; Ji et al. 2009). South of the suture, the Tethyan Sedimentary Series consists of Cambrian to Eocene sedimentary and very low-grade metasedimentary rocks, mainly composed of phyllites, limestones and quartzose sandstones (DeCelles et al. 2001; Najman et al. 2008). Lhasa basement rocks, Transhimalayan volcanic and ultramafic rocks, and Tethyan Sedimentary Series display different εNd and 87Sr/86Sr signals, which can be easily distinguished (Chu et al. 2006; Clift et al. 2006; Najman 2006; Najman et al. 2008).

In Myanmar, the Burma terrane basement is variously represented. The Gaoligong Belt, Slate Belt and Mogok Metamorphic Belt form a continuous strip of Palaeozoic sediments and low- to high-grade metamorphic rocks with large granitic intrusions, from the eastern Himalayan syntaxis to the Tenasserim highlands (see Fig. 1b; Mitchell et al. 2004; Searle et al. 2007; Xu et al. 2008). The Burmese terrane basement also crops out in central Myanmar (see e.g. Mitchell et al. 2007; Shi et al. 2009; Bannert et al. 2011), and in the core of the Indo-Burman Ranges (Maurin & Rangin 2009). The Burmese extension of the Transhimalayan arc is notably represented by the Baunmauk and Salingyi batholiths, and Mokpalin–Sit–Kisin diorites, which have positive εNd and low 87Sr/86Sr ratios (Zaw 1990; Mitchell et al. 2012). Compilation of isotopic data on other Burmese terrane basement rocks shows a range in values that is similar to those of the SE Asian continental blocks, with low εNd (between −3 and −15) and high 87Sr/86Sr ratios that may exceed values of 0.740 (Zaw 1990; Chen et al. 2002; Mitchell et al. 2007; Xu et al. 2008; Liu et al. 2009; Mitchell et al. 2012).
Other structural units are considered not have made significant contributions to the isotopic signal of the sediment sources, either because their exposure is insignificant in the direct drainage area or because their contribution to the solid load of the drainage system is not important. Further inland, the contribution of the

Quiangtang terranes of central Tibet to the sedimentary supply of the Pondaung–Yaw river system seems improbable, owing to their distal character and the presence of an early orographic barrier, formed by a proto-Tibetan Plateau (Wang et al. 2008). A contribution from the Shan–Thai block, linking the southwestern region of central Tibet and Myanmar, with their petrographical and isotopic properties, and data from this study

Table 2. Synthesis of the Eocene drainage provinces of central Tibet and Myanmar, with their petrographical and isotopic properties, and data from this study

| Source 1: magmatic arc source | Source 2: axial belt source |
|-------------------------------|----------------------------|
| Petrography and heavy minerals | Bulk-rock εNd | Bulk-rock 87Sr/86Sr | Key references |
| Pondaung Formation | Coarse-grained samples | Mudstones samples | Pondaung Formation |
| Yaw Formation | Coarse-grained samples | Mudstones samples | Yaw Formation |
| Sites of Ganle, Yarshe and Thaminchauk (Family 2) | Sites of Paukkaung, Pangan and Nyaungpinle (Family 1) | Sites of Ganle, Yarshe and Thaminchauk (Family 2) | Sites of Paukkaung, Pangan and Nyaungpinle (Family 1) |
| Oligocene formations (Padaung and Shwezetaw) | Miocene formations (Kyaunkkok and Irrawaddy) | Oligocene formations (Padaung and Shwezetaw) | Miocene formations (Kyaunkkok and Irrawaddy) |
| Central Tibet domain | Lhasa terrane basement | Transhimalayan arc | Tethyan Sedimentary Series |
| Source 1: magmatic arc source | Source 2: axial belt source |
| Petrography and heavy minerals | Bulk-rock εNd | Bulk-rock 87Sr/86Sr | Key references |
| Lhasa terrane basement | S-type granitoids, Palaeozoic to Mesozoic metasediments | −10 to 0 | 0.706–0750, commonly >0.709 | Clift et al. 2001; Chu et al. 2006; Wu et al. 2010 |
| Transhimalayan arc | Volcanic rocks, I-type granitoids, ophiolites | +1 to +8 | <0.708 | Chung et al. 2005; Ji et al. 2009 |
| Tethyan Sedimentary Series | Sedimentary and low-grade metamorphic lithic fragments | −17 to −13, rarely −19 to −5, average −15 | 0.706–0750 | White et al. 2002; Najman et al. 2008 |
| Myanmar domain | Burma terrane basement | Burmese arc | Pondaung and Yaw Fm |
| Source 1: magmatic arc source | Source 2: axial belt source |
| Petrography and heavy minerals | Bulk-rock εNd | Bulk-rock 87Sr/86Sr | Key references |
| Burma terrane basement | Ultramafic rocks, low- and high-grade metamorphic rocks, S-type granitoids, Palaeozoic to Mesozoic metasediments | −13 to −3 | 0.706–0750, commonly >0.709 | Zaw 1990; Chen et al. 2002; Chu et al. 2006; Xu et al. 2008; Liu et al. 2009; Mitchell et al. 2012 |
| Burmese arc | Volcanic rocks, I-type granitoids | 0 to +8 | <0.708 | Zaw 1990; Mitchell et al. 2007, 2012 |
| Source 1: magmatic arc source | Source 2: axial belt source |
| Petrography and heavy minerals | Bulk-rock εNd | Bulk-rock 87Sr/86Sr | Key references |
| Source 1: magmatic arc source | Mainly volcanic lithic clasts | Metamorphic and sedimentary lithic clasts, low-grade metamorphic and ultramafic minerals | −3.8 to +0.3 | 0.705–0.711 | This study |
| Source 2: axial belt source | Metamorphic and sedimentary lithic clasts, low-grade metamorphic and ultramafic minerals | −7.8 to −3.9 | >0.714 |

Data compilations are available in the key references.
Fig. 6. Schematic map of sedimentary supply in the proto-Bay of Bengal at the time of deposition of rocks belonging to the Pondaung and Yaw Formations. ITSZ, Indus–Tsangpo Suture Zone; CMB, Central Myanmar Basin; TSS, Tethyan Sedimentary Series; IBR flysch, Indo-Burman Ranges flysch.

Discussion and conclusion: a former Tsangpo–Irrawaddy river connection?

Petrographic and isotopic results suggest a dual source for the Pondaung–Yaw drainage system; namely, the Asian magmatic arc and the Asian basement terranes. Distal (Tibetan) or proximal (Burmese) sources are isotopically and petrographically difficult to distinguish, because the two regions share similar features.

However, palaeoflow measurements indicate an eastern provenance for the Pondaung–Yaw river system. The disorganized stratigraphic shifts in sediment provenance and the isotopic discrepancies between marine and onshore fluviodeltaic sediments suggest a quickly evolving river system with local catchments rather than a long transport distance. A local provenance is supported by the presence of numerous pebble lags in the Pondaung successions. In addition, the presence of low-grade metamorphic rock fragments is consistent with a local source, because such fragments are found in abundance in the Burma terrane basement, but crop out only rarely in the Tibetan Lhasa terrane. The assemblage of volcanic arc and axial belt detritus is in accord with the local unroofing of an Andean-type cordiller (Garzanti et al. 2007), which extended along the Burmese margin during the Palaeogene and experienced an early episode of uplift (Morley 2004). The Pondaung and Yaw deposits are therefore better explained as resulting from the progressive exhumation and erosion of the local Burmese Andean-type margin, rather than from the distal Tibetan area.

The isotopic and petrographic results for the Pondaung and Yaw sediments, and the orientation of the two former delta systems, support a source in the Burmese margin for the Palaeogene flysch of the Indo-Burman Ranges, as proposed by Allen et al. (2008). Differences in lithic content between the flysch sample and the Pondaung–Yaw samples (see Fig. 4) suggest temporal and/or spatial variations in volcanic supply along the Burmese margin. Further west, in the proto-Bengal fan deposits, the arrival of small amounts of arc-derived material occurred sometime between 50 and 38 Ma (Kopili Formation), but seismic evidence of a dominant input from the NW suggests that these deposits are more likely to be from the Transhimalayan rather than the Burman portion of the arc (Najman et al. 2008). The Burmese subduction trench might have acted as a trap for offshore Burmese-sourced detritus, preventing the contribution of any Burmese sediment to the proto-Bengal fan. Despite the subordinate Transhimalayan contribution, Bengal Palaeogene sediments display a predominantly Indian cratonic provenance, with a minor component of the Tethyan Sedimentary Series in the Late Eocene–Early Miocene Barail Formation (Najman et al. 2008). The paucity of Tibetan input in the proto-Bengal fan and central Myanmar Eocene deposits, although puzzling, is not necessarily suggestive of the absence of Tibetan supply into the Bay of Bengal, as such sediments may have been deposited in the remnant ocean basin trapped between the Indian craton and the Burmese block, and later subducted below the Indo-Burman Ranges (see Fig. 6; Uddin & Lundberg 1998b; Najman et al. 2008). Potential Tibetan contributions in the northern end of the Chindwin Sub-Basin, where we did not sample, cannot be completely excluded, but their contribution to the general sedimentary supply into central Myanmar would have been insignificant.

Could an ephemeral Burmese–Tibetan connection have existed, in the Oligocene, before the Early Miocene divergence of Tsangpo and Irrawaddy fish fauna (Ruber et al. 2004)? Oligocene and Early Miocene series of the Central Myanmar Basin are unfortunately either poorly studied or poorly exposed (Bender 1983). Sedimentation rates in central Myanmar reached their lowest level in the Oligocene (Metivier et al. 1999); this suggests that
if a connection existed, it would not have supplied significant quantities of sediments.

Our integrated study of the Pondaung and Yaw Formations showed that during Late Middle Eocene to Early Oligocene times, central Myanmar was open to the Indian Ocean, and was the locus of SW-directed deltas, most probably sourced in the proximal highlands along the SE Asian shoreline. The Pondaung and Yaw deltaic systems are interpreted as supplied by the unroofing of an Andean-type cordillera that extended along the Burma terrane, representing the earned abandonment of the Transhimalayan arc. A potential Tibetan contribution to the sedimentary supply of central Myanmar appears unlikely. A connection between the Tibetan Plateau and central Myanmar before the Neogene shifts in SE Asian river networks, as suggested by former studies, seems not to have been recorded in the Pondaung–Yaw system.

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