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Provenance of the Tertiary sedimentary rocks of the Indo-Burman Ranges, Burma (Myanmar): Burman arc or Himalayan-derived?

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Abstract: The Indo-Burman Ranges in western Myanmar extend along the Sunda Arc subduction zone and may be divided into a western portion of Neogene sedimentary rocks and an eastern portion of Palaeogene sedimentary rocks, separated by the Kaladan Fault. Both Himalayan and Burman sources have been proposed for these sediments. Our thermochronological analyses on detrital grains, isotopic analyses on bulk rock, and petrographic and heavy mineral data indicate that the Palaeogene Indo-Burman Ranges contain a significant component of arc-derived material, interpreted as derived from the Burmese portion of the Mesozoic–Tertiary arc to the east. And older crustal component is also identifiable, which may have been sourced from the Himalaya or the Burmese margin. By contrast, the Neogene Indo-Burman Ranges show dominant derivation from the Himalaya. A minor arc-derived component may have been sourced from the Trans-Himalaya, or recycled from the arc-derived Paleogene Indo-Burman Ranges.

The Himalayas provide a type example of orogenesis, on which a number of current models of crustal deformation are based (Tapponier *et al*. 1982; Grujic *et al*. 1996, 2002; Beaumont *et al*. 2001, 2004; Jamieson *et al*. 2004). A knowledge of the erosional response of the orogen since collision (commonly taken at *c*. 55–50 Ma; Garzanti *et al*. 1987; Klootwijk *et al*. 1992; Searle *et al*. 1997) is important for discriminating between these various models, which differ in the timing and extent of associated erosion (Grujic *et al*. 1996, 2002; Beaumont *et al*. 2001, 2004; Jamieson *et al*. 2004; Tapponier *et al*. 1982; Replumaz & Tapponier 2003; Aitchison *et al*. 2007). Knowledge of the timing of the onset of significant erosion is also critical to evaluating the hypothesis that exhumation of the Himalayas influenced Tertiary global cooling (Raymo & Ruddiman 1992; Molnar *et al*. 1993) and the marked increase in marine ^{87}Sr/^{86}Sr ratios at *c*. 40 Ma (Richter *et al*. 1992). However, evidence for significant Palaeogene erosion from the southern flanks of the eastern and central Himalayas, particularly to eastern repositories, remains elusive. A large proportion of the Oligocene is represented in the foreland basin by a hiatus (DeCelles *et al*. 1998*a*; Najman *et al*. 2004), whereas a Palaeogene sequence of sediments is preserved in the Indus Fan, which may record early Himalayan erosion from the western part of the orogen (Qayyum *et al*. 1997; Clift *et al*. 2001). Poor age control prevents precise dating. Possible Oligocene strata in the Bengal Fan are currently inaccessible, with rocks from the base of the Ocean Drilling Program (ODP) legs 116 and 121 drill holes being dated at *c*. 17 Ma (Curray 1994; Galy *et al*. 1996). This paper seeks to find an early record of Himalayan erosion, preserved in the Indo-Burman Ranges of western Myanmar (Burma), as suggested by Curray *et al*. (1979) and others.

The Cretaceous–Palaeogene Indo-Burman Ranges of western Myanmar lie eastward of the subduction zone that runs from the Himalaya to the north to Sumatra to the south. The Indo-Burman Ranges continue westward as the Neogene Indo-Burman Ranges and the Chittagong Hill Tracts of Bangladesh, and sit approximately along the line of the subduction zone (Fig. 1). This west-vergent range has been interpreted as an accretionary prism, formed during subduction of the Indian plate beneath the Eurasian plate, by the offscraping of material of a proto-Bengal Fan, supplied from the emerging Himalaya to the north (Curray *et al*. 1979; Bender 1983; Hutchinson 1989; Curray 2005). As such, the prism sediments should show orogenic input from the time of Bengal Fan initiation. However, the time of initiation of sedimentation in the Bengal Fan is itself poorly constrained. Curray & Moore (1971) and Moore *et al*. (1974) noted a hiatus in seismic data that separates pre-fan from interpreted fan sediments of probable *c*. Palaeocene to mid-Eocene age. Sedimentation rates noticeably increased in the Oligocene (Curray & Moore 1971; Moore *et al*. 1974; Curray *et al*. 1979; Curray 1994), and in the Eocene for the proximal fan (Davies *et al*. 1995), with sedimentation continuing to the present day. The sedimentary rocks of western Myanmar are therefore potentially important in understanding the tectonics and the dynamics of erosion of the Himalaya, as the record of Himalayan-derived sediments older than Miocene is limited in the foreland basin, and inaccessible beyond 17 Ma for study in the Bengal Fan. However, the status of the Palaeogene Indo-Burman Ranges as accretionary prism material derived from the

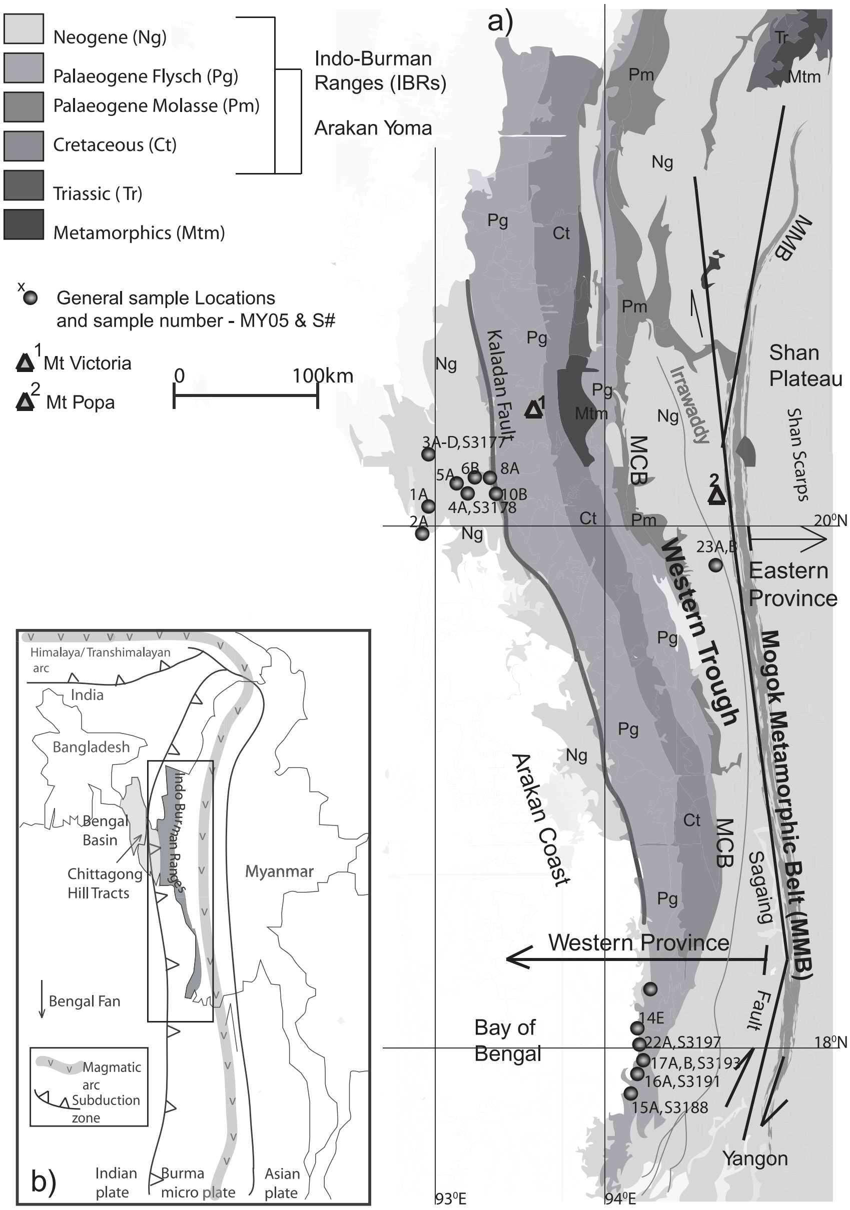

Fig. 1. Simplified geological map of western Myanmar (**a**) showing generalized sample locations for which the global positioning system references are given in the supplementary material. The Mogok Metamorphic Belt (MMB), Myanmar Central Basin (MCB), Irrawaddy River and divide between the Palaeogene and Neogene Indo-Burman Ranges are of note. The major notable and tectonic features of the region (**b**) include the Bengal Fan, plate boundaries, the magmatic arc and the India–Asian subduction zone. Adapted from Bender (1983).

rising Himalaya has been disputed by Mitchell (1993), who inferred that the Indo-Burman Ranges were derived from a magmatic arc that lies to the east (Fig. 1).

The petrographic and isotopic data presented here (Table 1) provide insight into the depositional history, source exhumation and provenance of the sedimentary rocks of western Myanmar. To assess provenance we have compared our data with published data for the approximately coeval foreland and remnant ocean basin deposits of known Himalayan derivation (Table 2; Robinson *et al*. 2001; DeCelles *et al*. 2004; Najman *et al*. 2005, 2008; Bernet *et al*. 2006; Szulc *et al*. 2006), Himalayan bedrock (DeCelles *et al*. 1998*a*, *b*, 2000) and rocks of the Jurassic–Tertiary magmatic arc of Myanmar (United Nations 1978*a*, *b*; Barley *et al*. 2003; Searle *et al*. 2007).

Overview of the geology of western Myanmar

Myanmar is located on the eastern edge of the zone of Himalayan convergence, south of the eastern Himalayan syntaxis where the NE–SW-striking structures of the Himalayan mountain chain rapidly change strike to a north–south orientation (Fig. 1). The region represents the transition zone between the Himalayan collision belt and the Indonesian arc where the Indian plate is at present subducting under Asia.

Most of western Myanmar is situated on the Burma microplate, interpreted by some as a forearc sliver (Fitch 1972; Curray *et al*. 1979; Pivnik *et al*. 1998; Bertrand & Rangin 2003), and bordered on the east by the Sagaing dextral strike-slip fault. It is a long-lived active margin, expressed in arcs of the Mogok Belt of Jurassic to Eocene age (Barley *et al*. 2003) and a younger (Miocene to Recent) arc of the Mount Popa Region to the west (Fig. 1), active during recent stages of eastward subduction and associated with the Andaman Sea spreading centre (Stephenson & Marshall 1984). The Mogok Belt is considered an extension of the Transhimalayan arc and Lhasa terrane (Mitchell 1993; Mitchell *et al*. 2007; Searle *et al*. 2007), which runs through the Himalaya to the north, marking the ancient Asian active margin, and abruptly changes to a north–south orientation at the eastern

Himalayan syntaxis. To the west of the arc in Myanmar, the Western Trough is considered to be a forearc basin (Mitchell 1993; Pivnik *et al*. 1998; Bertrand & Rangin 2003), which extends furthest west into the Indo-Burman Ranges and itself can be divided laterally into an eastern Palaeogene and a western Neogene belt, separated by the Kaladan Fault. The eastern Palaeogene belt preserves a sequence of predominantly Palaeogene sediments with Carnian feldspathic turbidites, local ophiolite, and metamorphic rocks of Triassic to Cretaceous age and a mica schist belt up to 30 km wide (Brunnschweiler 1966; Bender 1983; Mitchell 1993). The Neogene western belt is predominantly composed of Neogene flysch-type sediments with minor deformed Campanian and Maastrichtian (*c*. 83–65 Ma) pelagic limestones and shales, which crop out in the furthest western parts of the Ranges as well as on offshore islands of the Arakan coast, and continue along strike into Bangladesh (Bender 1983; Mitchell 1993). The southernmost portion of the Indo-Burman Ranges, and the region from which samples have been collected, is often referred to as the Arakan Yoma and this is a name used hereafter (see also Fig. 1).

Approach and methods

The two possible sources for the Palaeogene and Neogene Indo-Burman Ranges are the eastern Himalaya (including Indian crust metamorphosed during the Tertiary orogeny, and the Cretaceous–Palaeogene Transhimalayan arc of the Asian plate) (Mitchell 1974; Curray *et al*. 1979; Hutchinson 1989) and Burmese margin dominated by the Burmese arc (Mitchell 1993). Their contrasting ages and lithologies are reflected in different petrographic, mineralogical, isotopic and mineral age characteristics. A combination of published Himalayan bedrock data and data from the Himalayan-derived foreland basin and Bengal Basin sediments is used to characterize the signature of material eroded from the southern flanks of the rising Himalayan thrust belt through time. These petrographic and isotopic data show that the Indian crustal material is distinct and easily distinguished from the late Jurassic to Eocene magmatic arc that lies to the east of the Indo-Burman Ranges and stretches south through Myanmar to Sumatra, as well as NW into the Himalaya as the Transhimalaya of the Asian plate (Mitchell 1993).

We undertook analyses on a total of 14 samples (data and details of methods are available at http://www.geolsoc.org.uk/SUP18319) from the Palaeogene and Neogene Indo-Burman Ranges and compared them with published data from the Himalaya and Burma to identify provenance of the rocks. Where available, Palaeogene and Neogene bedrock was sampled. However, poor exposure has also necessitated sampling of modern river sands and muds. Modern river sediments provide an efficient average sample of exposed crust in the river catchment even though the precise location of the source rock is unknown.

Multiple proxies are used to obtain the best image of source provenance and to avoid potential bias that may arise by relying on a single mineral type. All data tables and methods are given in the supplementary material. A heavy mineral and petrographic study (see supplementary material) was performed on all samples from the Palaeogene and Neogene and was used as the first step in identifying the provenance of the samples. Detrital zircons were used for fission-track analysis (see supplementary material) and U–Pb dating using laser ablation inductively coupled plasma mass spectrometry in two laboratories (see supplementary material). Zircons have a closure temperature for fission-track analysis of *c*. 200–310 °C (Hurford 1986). Above this, fission tracks may partially or fully anneal. The higher closure temperature compared with apatite (*c*. 120 °C) makes this technique suitable for provenance work, as the zircon fission-track grain ages are not as susceptible to resetting at burial temperatures. The ages obtained represent cooling in the source region (Carter 1999). The U–Pb system has a much higher closure temperature for zircon and is stable to *c*. 750 °C (e.g. Spear & Parrish 1996), beyond which uranium is lost. Zircon U–Pb ages from detrital grains in a sedimentary rock are therefore considered to be primary crystallization or metamorphic ages. ^{40}Ar–^{39}Ar dating of detrital micas was undertaken on Neogene samples (see supplementary material), but not on the unmicaceous Palaeogene samples. Data were collected using a GVi instruments Argus multi-collector mass spectrometer with a variable sensitivity Faraday collector array in static mode. White mica has a closure temperature of *c*. 350 °C in the Ar–Ar system (e.g. McDougall & Harrison 1999) and as such also records post-metamorphic cooling in the source region, making ^{40}Ar–^{39}Ar dating and fission-track analysis highly compatible for provenance determination of clastic sequences. Modern river muds were used for whole-rock Sm–Nd isotope fingerprinting. Isotope ratios were measured on a T40 sector 54 VG thermal ionization mass spectrometer using a triple filament assembly (see supplementary material). The ϵ_{Nd} value reflects the age and composition of the source rock, ranging from very negative values for old crustal rocks to positive values for younger igneous rocks.

Results

Isotopic and petrographic data from the Palaeogene Indo-Burman Ranges

The data presented in Table 1 and summarized below were obtained from Palaeogene bedrock, samples of modern rivers draining the Palaeogene Indo-Burman Ranges and pebbles taken from a modern river draining the bedrock at the border between the Palaeogene and Neogene Indo-Burman Ranges (Fig. 1). Petrographic point-count data from the pebbles extracted from a modern river, and bedrock data, are presented in Figure 2. The bedrock petrographic data show a significant proportion of volcanic lithic detritus and on the standard QFL plot of Dickinson (1985) plot within the Magmatic Arc province. The pebbles plot mostly within the Recycled Orogen province of the QFL; however, the lithic plot (Fig. 2b) shows that the pebbles incorporate a mixture of sources from orogenic to magmatic arc, as indicated by the percentage of low-grade metamorphic lithic and volcanic lithic fragments, respectively.

Bulk-rock Sm–Nd data show consistent $\epsilon_{\mathrm{Nd}}(0)$ values of *c*. −4.0, for samples from three rivers draining Palaeogene bedrock (Fig. 3). Zircon fission-track data (Fig. 4) from bedrock and modern river sands show dominant Palaeogene and Cretaceous age populations with minor contribution of Palaeozoic grains. U–Pb dating on detrital zircons (Fig. 5) shows predominant zircon populations of Palaeocene–Cretaceous (*c*. 55–150 Ma) and Cambro-Ordovician and Precambrian age. Rare Neogene grains appearing in modern river samples and one Palaeogene bedrock sample in both the fission-track data and U–Pb data probably reflect drainage through some small Miocene bedrock exposure, and analytical contamination in the case of the bedrock sample.

Isotopic and petrographic data from the Neogene Indo-Burman Ranges

The data presented in Table 1 alongside the data from the Palaeogene Indo-Burman Ranges were obtained from Neogene

Table 1. *Data from the Palaeogene and Neogene Indo-Burman Ranges, and the Irrawaddy River*

Location	Rock description, heavy minerals and petrography	Whole-rock Sm–Nd $\epsilon_{Nd}(0)$	Zircon U–Pb ages	^{40}Ar–^{39}Ar ages of white mica	Zircon fission-track ages
Palaeogene Indo-Burman Ranges (east); data from bedrock, modern rivers draining Palaeogene bedrock and pebbles in these rivers	Fine-grained mudstones, silts and sstn, thin turbidites and micritic limestones. Bedrock is volcanic lithic and plots within Magmatic Arc province of QFL plot (Dickinson 1985), modern river samples represent a continuum of arc provenance to recycled orogen with low-grade metamorphic to volcanic lithics. Few heavy minerals.	−4.0, −4.1 and −4.2	Predominant age peaks at 70–150 Ma and 500–2800 Ma with a recurring subordinate population at 42–60 Ma	Unmicaceous	Palaeogene and Cretaceous populations, with minor Palaeozoic input
Neogene Indo-Burman Ranges (west); data from bedrock	Medium-grained sstn and mdst. Low-grade metamorphic lithic fragments plot within Recycled Orogen province of QFL plot. Common garnet	−10.7 and −12.2; −7.3 for a sample on the border between the Palaeogene and Neogene Indo-Burman Ranges	Main age peaks 500–2800 Ma (80–96% of all grains); grains with ages <150 Ma make up 0–15% of total grains per sample	Main age component <55 Ma (up to 100% of grains)	Major Oligo-Miocene age peaks <55 Ma with up to 100% of grains <55 Ma. Older ages of >200 Ma and 60–150 Ma are subordinate
Irrawaddy River modern river sediment (draining the Burman margin including the Indo-Burman Ranges, the Mogok Metamorphic Belt and the Central Basins, and eastern Himalayan syntaxis)	Plots within Recycled Orogen province of QFL plot	−8.3 (see also Table 2)	See Table 2	<55 Ma grains make up 89% of the sediment; 7% arc-aged grains of *c.* 70–150 Ma, and 4% >200 Ma	Tertiary ages make up 74% of the sample; arc-aged component *c.* 25%

bedrock in western Myanmar and from a modern river draining Neogene bedrock, both in the westernmost portion of the Indo-Burman Ranges, which extends along strike into eastern Bangladesh (Chittagong Hill Tracts) as shown in Figure 1.

Petrographic data from Neogene bedrock samples are presented in Figure 2. All of the samples plot within the Recycled Orogenic province of the standard QFL plot (Fig. 2a) of Dickinson (1985). Lithic composition (Fig. 2b) shows a predominance of low-grade metamorphic lithic fragments. The Metamorphic Index ranges from 100 to 250 (where zero is non-metamorphic and 500 is high grade; (see supplementary material)), indicating occurrence of very low-grade (slate) to medium-grade (micaceous schist) metamorphic lithic fragments. Plentiful garnet in the Neogene samples is further indication of a medium-grade metamorphic component. It is noteworthy that the occurrence of garnet diminishes eastward towards the Palaeogene Indo-Burman Ranges border. Sm–Nd fingerprinting gives $\epsilon_{Nd}(0)$ values of −10.7 and −12.2 for two Neogene sandstones and a lower value of −7.3 for one sample on the border of the Palaeogene and Neogene Indo-Burman Ranges (Fig. 3). Detrital zircon fission-track data obtained from four Neogene bedrock samples all show major Oligo-Miocene age populations and Cretaceous grains are minor. Eastwards towards the Palaeogene Indo-Burman Ranges, the proportion of Tertiary grains decreases in the zircon fission-track data and grains with ages >200 Ma increase, as does the proportion of grains aged 56–150 Ma (from zero to 40% of total number of grains, Fig. 4a). U–Pb dating of detrital zircons (Fig. 5) shows that the dominant age population is 500–2800 Ma, and Cretaceous grains are present but few (4–6% of total grains in samples with 65–90 grains analysed). ^{40}Ar–^{39}Ar dates were obtained from detrital white mica from two samples (in other Neogene samples the micas were too small for analysis). The first sample is taken from the Arakan coast (Sittwe Point), which runs along strike into the Chittagong Hill Tracts of eastern Bangladesh, and represents the most westerly sample in the Neogene of the Indo-Burman Ranges. In this sample 100% of the grains yielded ages <55 Ma, with a youngest age of 13 Ma. The second sample is the most easterly in the Neogene Indo-Burman Ranges on the boundary between the Neogene and Palaeogene. Although this is a small dataset, Tertiary ages of <55 Ma form the largest age mode (43%) and the youngest detrital age is 29 Ma (Fig. 4a).

Interpretations of provenance

To determine the provenance of the Palaeogene and Neogene Indo-Burman Ranges, it is necessary to compare our data with published data for the proposed source regions of the Himalaya and Burma. These characteristics are presented fully in Table 2 and summarized briefly below.

Characteristics of the proposed source regions for the Indo-Burman Range sedimentary rocks: Himalayan and Burman margin

Data from the peripheral foreland basin provide the source signature of detritus eroded from the southern flank of the Himalaya and are a valuable source of information on erosion of the hinterland that has been lost in the hinterland itself because of metamorphic overprinting. The Himalayan detritus from the peripheral foreland and remnant ocean basins (Table 2) in India, Nepal and Bangladesh contains minerals with predominantly Tertiary but subordinate pre-Tertiary cooling age populations as seen in ^{39}Ar–^{40}Ar ages of detrital white micas and zircon

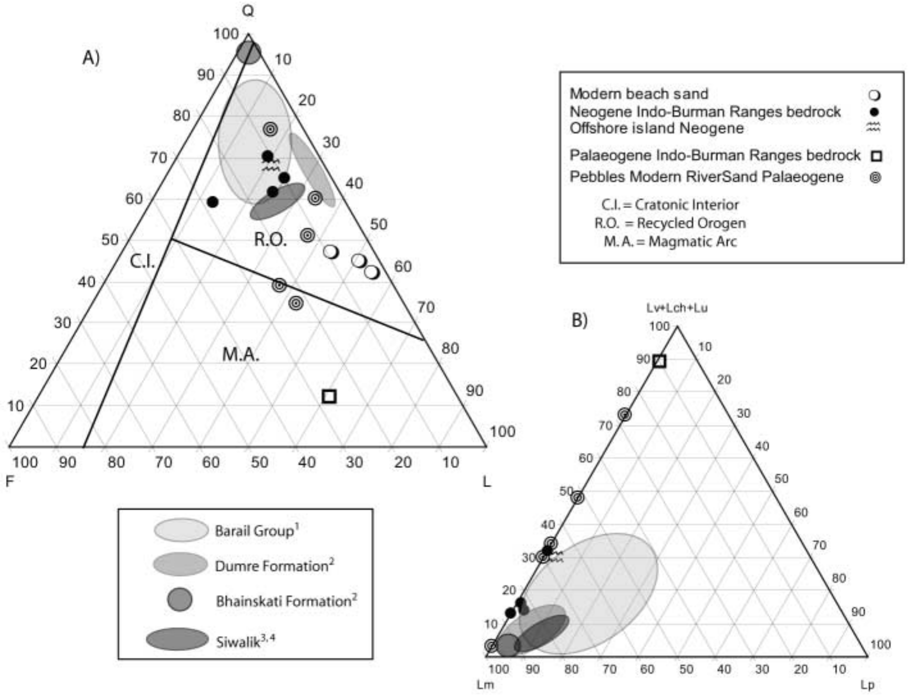

Fig. 2. (**a**) QFL and (**b**) lithic plot for Palaeogene and Neogene samples from the Indo-Burman Ranges compared with petrographic assemblages of the Oligocene Barail Formation of the Bengal Basin, and Himalayan foreland basin rocks of the Eocene Bhainskati Formation, the Miocene Dumre Formation and the Miocene to Recent Siwalik Group. Circled regions showing the Bhainskati, Dumre and Siwalik Formations are based on the data for each, incorporating minimum and maximum values. Q, quartz; F, feldspar; L, lithic fragments (Lm, metamorphic; Lp, pelitic; Lv, volcanic; Lch, chert; Lu, ultramafic). Sources: 1, Najman *et al*. (2008); 2, Najman *et al*. (2005); 3, DeCelles *et al*. (1998*a*); 4, Szulc *et al*. (2006).

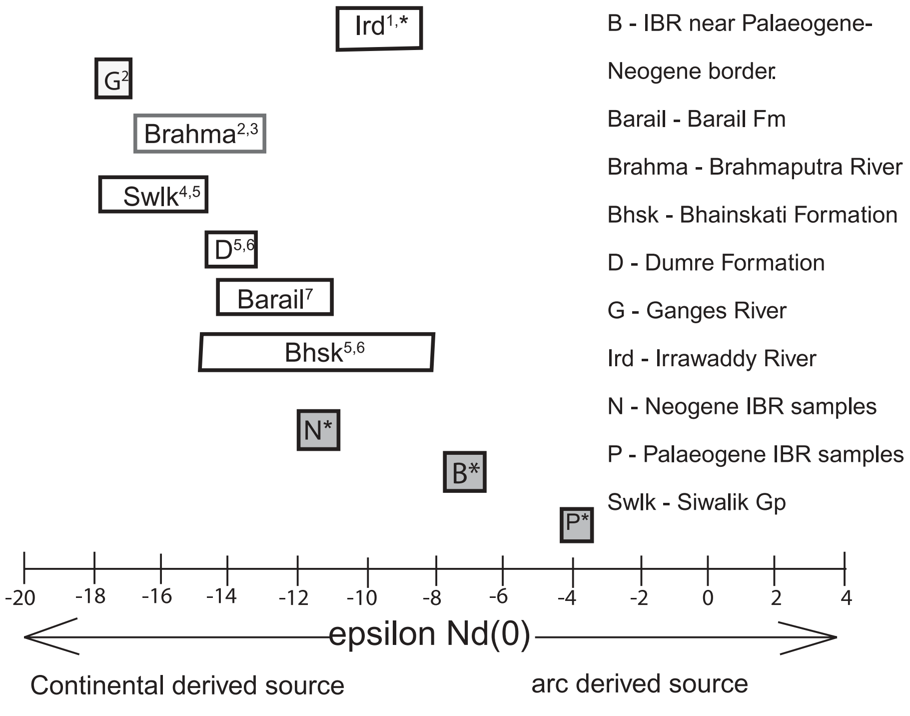

Fig. 3. $\epsilon_{Nd}(0)$ values for Palaeogene and Neogene samples from the Indo-Burman Ranges (IBR) compared with data from the Himalayan-derived foreland and remnant ocean basin rocks (Bhainskati Formation, Dumre Formation, Barail Formation and Siwalik Group) as well as modern river samples from the Irrawaddy, Ganges and Brahmaputra. A crustal source with a subordinate arc-derived component is indicated by the weakly negative ϵ_{Nd} values for the Palaeogene Indo-Burman Ranges and is in contrast to our Neogene Indo-Burman Ranges samples and Himalayan foreland basin detritus, which show dominantly continental derivation as indicated by their more strongly negative values. One sample (MY05 8A) was taken from the boundary between the Palaeogene and Neogene Indo-Burman Ranges and its ϵ_{Nd} value of -7.3 reflects an intermediate composition between Palaeogene and Neogene samples. Sources: 1, Colin *et al.* 1999; 2, Galy & France Lanord 2001; 3, Singh & France Lanord 2002; 4, Szulc *et al.* 2006; 5, Robinson *et al.* 2001; 6, DeCelles *et al.* 2004; 7, Najman *et al.* 2008. *our data, this study.

fission-track ages from the Eocene Bhainskati (Sakai 1983; Najman *et al*. 2005), Oligocene Barail (Reimann 1993; Najman *et al*. 2008), Oligo-Miocene Dumre (DeCelles *et al*. 1998*a*, 2001) and mid-Miocene to Recent Siwalik (Bhatia 1982; Gautam & Fujiwara 2000; Bernet *et al*. 2006; Szulc *et al*. 2006) formations, representing erosion from metamorphosed core and unmetamorphosed cover of the Himalaya. U–Pb data for all these formations show that the majority of zircon grains have ages between 500 and 2800 Ma, and are consistent with data from Himalayan bedrock (DeCelles *et al*. 1998*a*, *b*) as well as data from the Ganges River, which drains the Himalaya (Campbell *et al*. 2005). ϵ_{Nd} data from the peripheral foreland basin range from -8 (Eocene Bhainskai Formation) to -16 (Miocene–Recent Siwalik Group), confirming a continental-

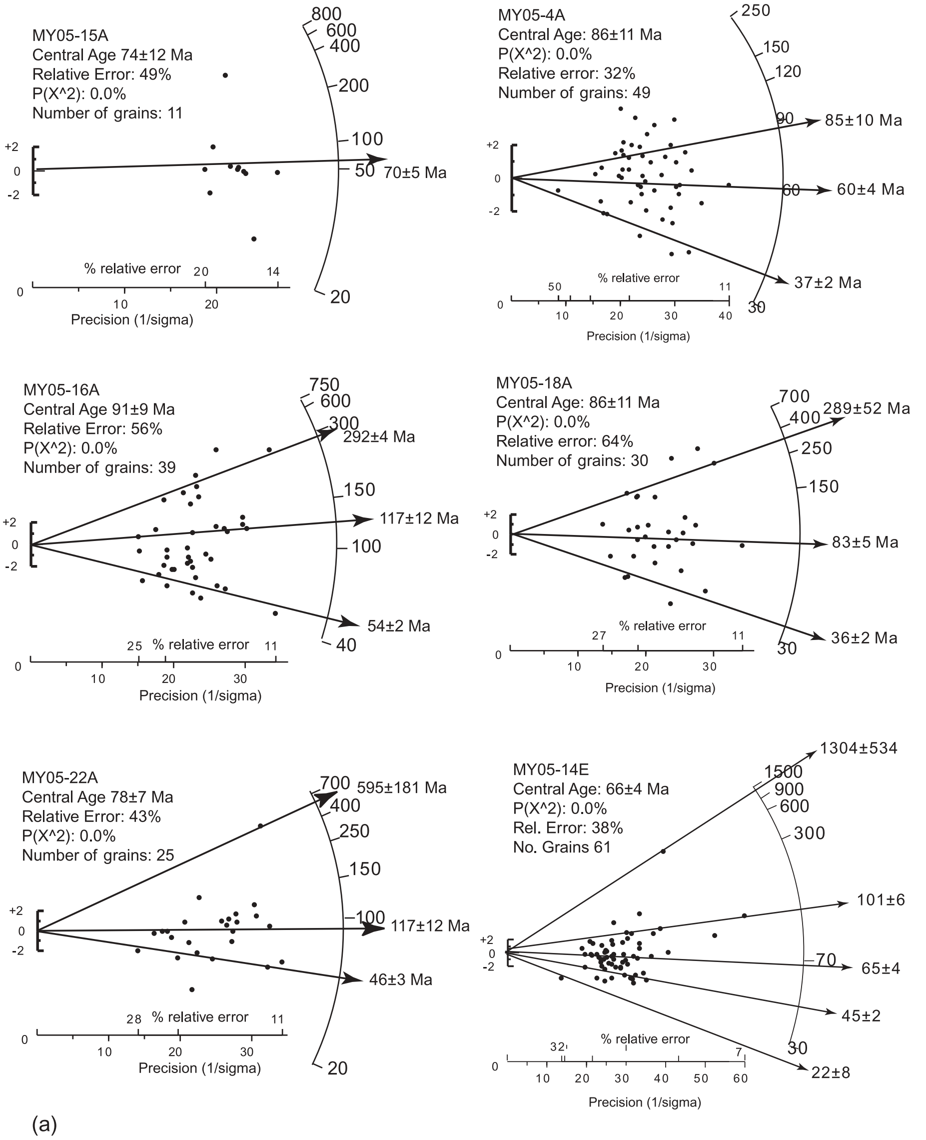

Fig. 4. Detrital zircon fission-track radial plots for data for the Palaeogene Indo-Burman Ranges (**a**) and zircon fission-track data and ^{39}Ar–^{40}Ar for the Neogene Indo-Burman Ranges (note: MY05-8A is Palaeogene) (**b**) with main population modes highlighted. The data show a predominance of arc-aged grains of 75–150 Ma in Palaeogene samples. However, younger populations as well as small older populations are also represented and are attributed to a subordinate continental source. The Neogene samples show a predominance of ages less than 55 Ma. ^{39}Ar–^{40}Ar white mica data are presented for samples furthest west (MY05 2A) in the Neogene Indo-Burman Ranges and furthest east (MY05 10B). In the radial plot the uncertainty in a single age estimate is isolated so that it is easier to judge the variation in ages between crystals. When multiple age populations are deduced in the radial plot of the sample data, statistical models can be applied to estimate the component ages, particularly the youngest age population. The vertical and horizontal axes represent the standardized age estimate and reciprocal error, respectively.

influenced source region with greater input from the suture zone during early stages of orogenesis (Robinson *et al*. 2001; DeCelles *et al*. 2004).

The Cretaceous–Tertiary Transhimalayan batholith (Singh *et al*. 2006), which occurs north of the suture zone and represents the ancient Asian active margin, made only a minor contribution to basins south of the orogen, as evidenced by the relative paucity of arc-derived material in the basin detritus as seen in Table 2 (DeCelles *et al*. 2001, 2004; Najman *et al*. 2005, 2008; Szulc *et al*. 2006). This ancient active margin continues south into Burma. United Nations (1978*a*, *b*) documented the typical age signature of Cretaceous arc magmatism based on K–Ar mineral dating of batholiths (Table 2). Barley *et al*. (2003) reported zircon U–Pb ages from I-type granitoids that confirm Andean-type granite magmatism was widespread along the Burma margin throughout the pre-collisional period in the Tertiary.

Although dominated by the Cretaceous–Eocene arc, the Burmese margin also contains material from crustal sources, which predate and were intruded by the arc and minerals of which were reset by Tertiary magmatism and metamorphism. The Burmese Margin includes the high ground of the Indo-Burman Ranges in the eastern belt composed of Triassic flysch and mica schists (Mitchell 1993). Data from the Burman margin, including our new data for the Irrawaddy River, are presented in Tables 1 and 2. Bertrand *et al*. (1999) reported mica ages spanning the Oligocene to middle Miocene from the

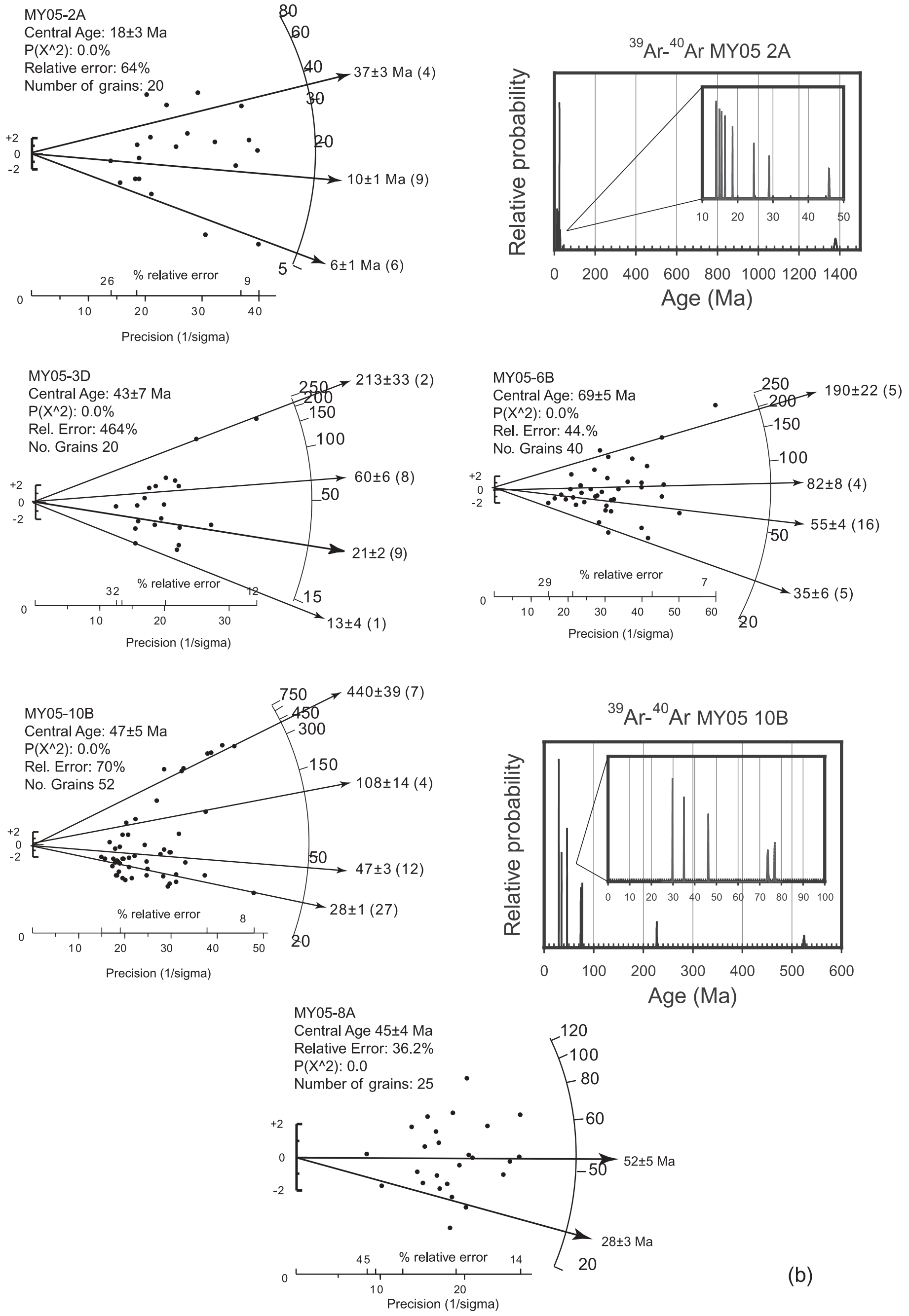

Fig. 4. (*continued*)

Shan Scarp alongside the Mogok Metamorphic Belt, and U–Pb data (Barley *et al*. 2003; Searle *et al*. 2007) have identified Tertiary aged zircons that confirm the presence of two distinct metamorphic events on the Burman margin, one at *c*. 59 Ma and a later phase that overprinted the former between *c*. 43 and 29 Ma. ^{39}Ar–^{40}Ar white mica data (Tables 1 and 2 and Fig. 6) from the Irrawaddy River, which drains the tip of the Himalayan eastern syntaxis as well as the Central Myanmar Basin, Mogok Belt and Indo-Burman Ranges, shows that Tertiary aged mica grains make up the bulk of the sediment. The majority of these grains are of Palaeogene age. The remainder is composed of Mesozoic arc-aged grains and grains older than 200 Ma. Over 70% of detrital zircon fission-track dates from the Irrawaddy bed load give Tertiary ages, whereas the arc-aged component represents *c*. 25% of total grains (Fig. 6). U–Pb zircon data from the Irrawaddy (Bodet & Schärer 2000) also give Tertiary aged grains with a similar proportion of ages falling in the arc-aged bracket of 56–150 Ma. Old grains up to a maximum of *c*. 1250 Ma are also present. ϵ_{Nd} values of *c*. −8.3 to −10.7 in the Irrawaddy River reflect mixed input from continental-derived (Himalayan and/or Burman margin) and arc-derived bedrock (Tables 1 and 2 and Fig. 3).

Provenance of the Palaeogene rocks of the Indo-Burman Ranges

Evidence of Cretaceous arc detritus in the Palaeogene Indo-Burman Ranges. The significant proportion of volcanic detritus

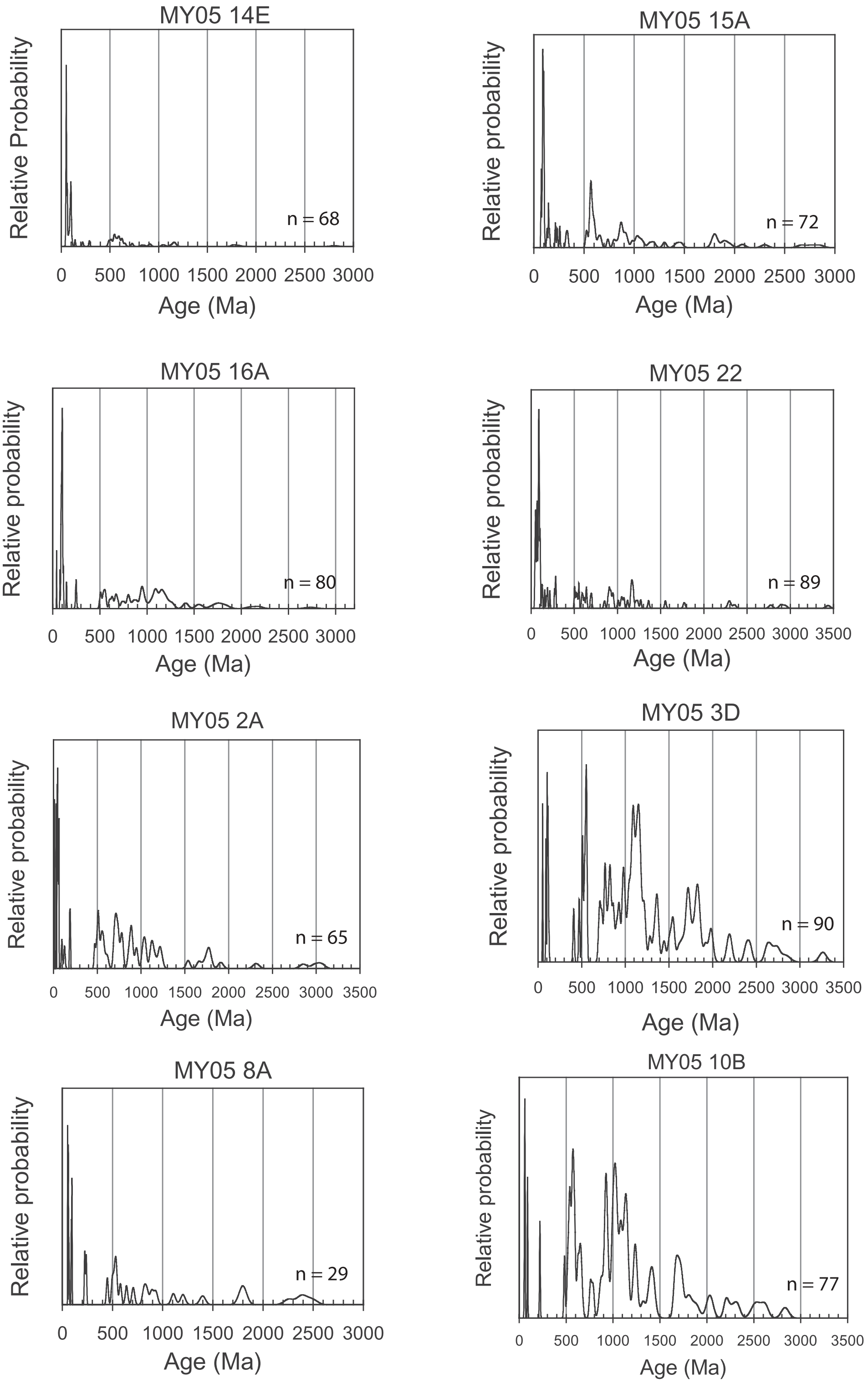

Fig. 5. Probability density plots for concordant detrital zircon ^{238}U/^{206}Pb ages from bedrock and modern river sediments from the Palaeogene and Neogene Indo-Burman Ranges. Top four panels are Palaeogene samples, bottom three panels are Neogene samples; MY05-8A is Palaeogene. Significant arc-aged populations of between 70 and 150 Ma are present within the Palaeogene samples, as well as Palaeogene grains and a large number of grains between 500 and 2800 Ma. Young grains of <20 Ma in modern river samples probably indicate drainage through small Miocene bedrock exposures. Neogene samples show only a limited number of grains between 70 and 150 Ma (maximum of four grains per sample), Palaeogene and Neogene grains, and with most ages spanning 500–2800 Ma.

Table 2. *Published data for the proposed source regions of the Himalaya and Burma*

Source region	Rock description, heavy minerals and petrography	Whole-rock Sm–Nd $\varepsilon_{\mathrm{Nd}}(0)$	U–Pb ages of zircon	^{40}Ar–^{39}Ar ages of detrital white mica	Detrital zircon fission-track data
Himalayan bedrock					
Himalayan bedrock southern flank (characteristics interpolated from foreland and remnant ocean basin sediments)					
Eocene; Bhainskati Formation (Nepal foreland basin)	Quartz arenites (1). Predominantly Tertiary, peak at 15–20 Ma. Ages span back to 1200 Ma (8).	−8 to −14.9 (2)	500–>3000 Ma. Rare Cretaceous grains (3)	Unmicaceous	Peaks at *c.* 343 Ma (59%), *c.* 119 Ma (21%) and 45 Ma (20%) (4)
Oligocene; Barail (Bangladesh) remnant ocean basin	Sedimentary and low-grade metamorphic lithic fragments. Recycled Orogen (5) on QFL of Dickinson (1985)	−11 to −14.6 (5)	Predominantly 500–>3000 Ma. Small Cretaceous population (5)	Palaeogene, Cretaceous, Cambro-Ordovician & Precambrian peaks (5)	Span Neogene to Lower Palaeozoic (5)
Miocene; Dumre Formation (Nepal foreland basin)	Metasedimentary lithic fragments. Recycled Orogen on QFL plot (1)	−14.5 to −13.1 (1)	500–>3000 Ma. Rare Cretaceous grains (3, 6)	All ages <55 Ma (7)	Peaks at 30 Ma (69–84%), 300–350 Ma (8–18%) and 60–120 Ma (6–8%) (4)
Miocene to Recent; Siwaliks (Nepal foreland basin)	Metamorphic lithic fragments, plagioclase and first appearance of high-grade metamorphic minerals in the Siwaliks. Recycled Orogen on QFL plot (6)	−14.6 to −18 (1, 8)	500–>2500 Ma (9)	Predominantly Tertiary, peak at 15–20 Ma. Ages span back to 1200 Ma (8).	Neogene & subordinate Cretaceous populations (9)
Bedrock signal today					
Modern river sediments	Higher Himalayan detritus dominates in major rivers.	Brahmaputra −12.5 to −16.9 (10, 11). Ganges −17.2 & −17.7 (10)	Data from the Ganges show dominance of Proterozoic to Palaeozoic ages and no grains between 55 and 125 Ma (12)	As determined from Gangetic tributaries: Neogene peak, subordinate grains ranging to Precambrian (13)	Gangetic tributaries: Neogene peak (9). He data: <55 Ma, Plio-Pleistocene peak (Ganges) (12)
Burma					
Magmatic arc	See below	No data available	Zircon U–Pb ages on I-type granitoids give ages of 120–150 Ma (14)	K–Ar mineral dating of batholiths gives cooling ages of 79–100 Ma (15)	No data available
Burman margin including region drained by the Irrawaddy River and area intruded by the arc. Data from modern Irrawaddy River sediment. Shan-Thai block lies to east, forearc–back-arc of Indo-Burman Ranges to west. Palaeocontinental margin	Cretaceous arc rocks and Triassic forearc–back-arc sediments on metamorphic basement. Mogok schists, gneisses and intrusive rocks, Shan-Thai Proterozoic–Cretaceous sedimentary rocks on schist basement. Irrawaddy River sediment plots in Recycled Orogen province of QFL plot (Dickinson 1985)	Irrawaddy River −10.7 (16); and −8.3 (this study)	U–Pb dating shows Tertiary aged zircons along the Burma margin (17); Irrawaddy U–Pb data peak at <55 Ma (30%) and 56–150 Ma (38%). Older grains present up to 1250 Ma (32%) (18)	Mica ages of 26–16 Ma along Shan Scarp (19). Palaeogene & Neogene, plus rare Cretaceous and Palaeozoic grains in Irrawaddy (this study).	Neogene, Palaeogene and Cretaceous populations in Irrawaddy sediment (this study).

(1) DeCelles *et al.* 1998*a*; (2) Robinson *et al.* 2001; (3) DeCelles *et al.* 2004; (4) Najman *et al.* 2005; (5) Najman *et al.* 2008; (6) DeCelles *et al.* 1998*b*; (7) DeCelles *et al.* 2001; (8) Szulc *et al.* 2006; (9) Bernet *et al.* 2006; (10) Galy & France-Lanord 2001; (11) Singh & France-Lanord 2002; (12) Campbell *et al.* 2005; (13) Brewer *et al.* (2003); (14) Barley *et al.* 2003; (15) United Nations 1978*a,b* cited by Mitchell 1993; (16) Colin *et al.* 1999; (17) Searle *et al.* 2007; (18) Bodet & Scharer 2000; (19) Bertrand *et al.* 1999.

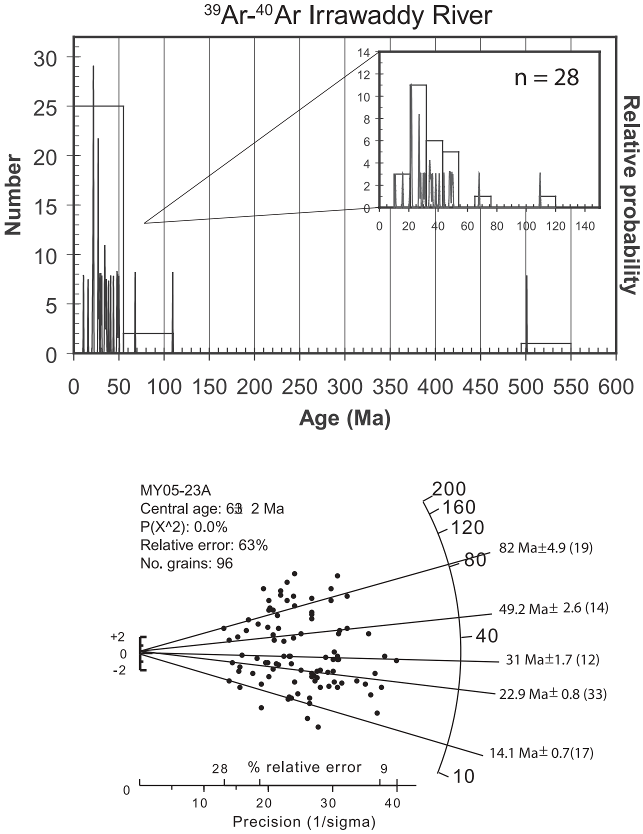

Fig. 6. ^{39}Ar–^{40}Ar white mica and zircon fission-track data for the modern Irrawaddy River. Both datasets show dominant Tertiary aged grains that make up 80–89% of the sample. The majority of these grains are Palaeogene with subordinate Neogene ages. A smaller but notable 'arc-aged' (*c*. 60–150 Ma) component is also present in the Ar–Ar white mica and zircon fission-track data (7% and 20%, respectively), which can be compared with U–Pb data of Bodet & Schärer (2000) where the arc-aged component is dominant and significant but subordinate Tertiary ages are also present. These data are to be expected in a large river that drains the corner of the eastern Himalayan syntaxis as well as the Mogok Metamorphic Belt, Myanmar Central Basin and Indo-Burman Ranges on the Burman margin.

in the bedrock sample as seen on the QFL plot (Fig. 2) is consistent with arc derivation. The pebbles from a modern river suggest that there is source mixing, indicated by the presence of pebbles with many low-grade metasedimentary lithic fragments (orogenic) and volcanic lithic fragments (arc).

River sediment samples draining the Palaeogene Indo-Burman Ranges along the southwestern coast with consistent ϵ_{Nd} values of −4 indicate significant, although not exclusive, derivation from arc sources. These values are less negative than data obtained by Colin *et al*. (1999) from analyses of sediments collected offshore of the Arakan Yoma, which have ϵ_{Nd} values of −8.6. We surmise that these more negative values may be the result of mixing with Bengal Fan material. Cretaceous aged zircons typical of arc derivation make up a significant proportion of the total zircon population. The zircon U–Pb data from the Palaeogene Indo-Burman Ranges show a significant component of typical arc ages from 70 to 150 Ma (14–36% of total grains). Detrital zircon fission-track data show a dominant population of grains at *c*. 56–120 Ma in five out of six samples, representing between 57 and 82% of the total number of grains per sample. In the remaining sample this age population makes up 32% of all grains.

All provenance data are consistent with the interpretation that the Indo-Burman Ranges contain a significant component of detritus derived from a Cretaceous–Palaeogene arc. This Cretaceous–Tertiary arc forms the Transhimalaya and then bends southward, through Myanmar to Sumatra (although the arc is not identified in the NE syntaxis, it reappears in Burma). The Burman extension of this arc is the most likely source of the Palaeogene Arakan Yoma (Indo-Burman Ranges) sedimentary rocks, in view of its proximity to the region. The possibility that the Yarlung Tsangpo (which drains the northern side of the Himalaya and Transhimalaya) may have routed to the South China Sea during this period (Clark *et al*. 2004), and the fact that, in contrast to the Palaeogene Indo-Burman Ranges, the Palaeogene Himalayan foreland and remnant ocean Bengal Basin Barail deposits show evidence of only minor arc-derived input (Table 2; ϵ_{Nd} values of the foreland and remnant ocean basins are more negative compared with the Palaeogene IndoBurman Ranges (Robinson *et al*. 2001; Najman *et al*. 2008) and the arc-aged component of the zircon population is subordinate (DeCelles *et al*. 2004; Najman *et al*. 2005, 2008)), is inconsistent with substantial Transhimalayan material being transported south of the orogen to eastern repositories at this time. An arc-derived component of the Indo-Burman Ranges detritus is in partial agreement with Chhibber (1934) and Mitchell (1993), who considered the Palaeogene Indo-Burman Ranges to be an equivalent or extension to the Western Trough forearc sediments of western Myanmar. Pivnik *et al*. (1998) believed this was later separated by the rising Mt. Popa arc, whereas Mitchell (1993) believed this separation was caused by the emplacement of older rocks in the east of the ranges in late Eocene or early Oligocene time.

Subordinate component of crustal-derived detritus in the Palaeogene Indo-Burman Ranges rocks. As well as the significant arc-derived component represented in the petrography, zircon U–Pb and fission-track data, and bulk-rock Sm–Nd, our data clearly show an additional continental source as identified in petrography by low-grade metamorphic and siltstone lithic fragments, by more negative ϵ_{Nd} values than expected for arc-derived rocks, and by zircons with U–Pb ages of 500–2800 Ma, and fission-track ages older than 300 Ma. This contribution forms between 2 and 71% of the detritus (2–15% zircons with such zircon fission-track ages, and 35–71% zircons with such U–Pb ages).

It could be argued that these grains are of Himalayan origin, as such age ranges (Table 2) are found in grains of the foreland basin Bhainskati Formation, whereas zircons from the modern Irrawaddy River, which drains the Burman margin and Indo-Burman Ranges, Central Myanmar Basins and Mogok Belt (as well as parts of the eastern Himalayan syntaxis), do not show evidence of U–Pb ages >1300 Ma (Bodet & Schärer 2000). Furthermore, the modern Irrawaddy River lacks the older fission-track age mode of >300 Ma. In a sample of 95 grains, 74% have ages <55 Ma, 24% are arc-aged between 59 and 130 Ma, and the remaining 2% have ages between 130 and 190 Ma. However, the isotopic characteristics of the Asian margin into which the arc intruded are incompletely characterized and differences between the terranes as currently proposed may be the result of sparse sampling. For example, 600 Ma grains have been found on the Burman margin and grains older than 1300 Ma in the Irrawaddy River sand (Liang *et al*. 2008). Thus, on the basis of available data, it is not possible to definitively differentiate between a Burmese margin and Indian Himalayan source for this older continental-derived component.

Provenance of the Neogene Indo-Burman Ranges

Comparison of our samples with the approximately coeval Dumre Formation (21–16 Ma) and the Siwaliks (15 Ma–Recent) of the peripheral Nepalese foreland basin allows an assessment of potential Himalayan provenance for the Neogene Indo-Burman Ranges.

Sediments from both the Dumre Formation and the Siwaliks plot within the Recycled Orogen province of the standard QFL plot. The predominance of metasedimentary lithic clasts provides evidence of derivation from the rising metamorphosed Himalayan fold–thrust belt, at first seen in the Dumre Formation and then in the Siwaliks (DeCelles *et al*. 1998*a*; Szulc *et al*. 2006). This is comparable with the petrographic data from the Indo-Burman Ranges Neogene samples, although potassium feldspar is noticeably higher in our samples (Fig. 2). $\epsilon_{\mathrm{Nd}}(0)$ values of -10.7 and -12.2 are indicative of a continental-derived source region but fall outwith the typical range of values for the modern Brahmaputra River, which drains the Himalaya and Trans-Himalayan arc, and outwith the values for the coalesced Ganges–Brahmaputra river (Galy & France-Lanord 2001; Singh & France-Lanord 2002). Values are also less negative than those from Miocene foreland basin rocks (Robinson *et al*. 2001), presumably because of a higher proportion of arc-derived detritus in the Neogene Indo-Burman Ranges. This difference is also seen in zircon U–Pb data where both foreland basin and Neogene IBR display Palaeozoic and Precambrian populations, but the Cretaceous arc aged grains are rare in the foreland basin but constitute up to 15% of the population in Neogene IBR samples (Fig. 5). Zircon fission-track and white mica ^{39}Ar–^{40}Ar ages in the Dumre Formation (DeCelles *et al*. 2001; Najman *et al*. 2005) and the Siwaliks (Bernet *et al*. 2006; Szulc *et al*. 2006) both show a predominance of grains with ages <55 Ma, which represent metamorphic cooling ages in the source region typical of the metamorphosed Higher Himalaya. This dominant age component of <55 Ma as seen in the Neogene foreland basin sediments is comparable with our data from the Neogene Indo-Burman Ranges (Figs 4 and 6).

Our data are consistent with a scenario where the dominant source region for the Neogene Indo-Burman Ranges was the rising Himalaya during the Miocene, detritus from which was incorporated into the proto-Bengal Fan, subsequently forming an accretionary prism at the subduction zone between the Indian and Asian plate. In contrast, we consider a dominant eastern, Burman, source unlikely. The unmicaceous very fine-grained sandstones and mudstones of the Palaeogene Indo-Burman Ranges have a dissimilar thermochronological, isotopic and petrographic signature to the rocks of the Neogene Indo-Burman Ranges, and could not have sourced the Neogene rocks. Further east, the Burmese arc margin is of Cretaceous age but nevertheless shows evidence of some grain age populations of both Tertiary and Palaeozoic–Proterozoic age, similar to those found in the Himalaya and Neogene Indo-Burman Ranges. However, it is unlikely that the Burma arc source to the east was a source to the Neogene Indo-Burman Ranges in view of the extremely limited extent of arc-derived material in the Neogene Indo-Burman Ranges and the fact that the Palaeogene Indo-Burman Ranges would have provided a barrier to transport of Burmese margin material westward by this time. Nevertheless, the Sm–Nd and zircon U–Pb data do show subordinate arc-derived input, greater than that seen in the Neogene Himalayan foreland basin sediments. This component may be recycled from the Palaeogene Indo-Burman Ranges, or may be from the Trans-Himalaya, transported during a time when such detritus made up a greater proportion of the load than is found in the snytaxially-dominated Brahmaputra today.

Constraints to the depositional age and time of exhumation of the Indo-Burman Ranges

The Palaeogene Indo-Burman Ranges. Fission-track dating on modern river sediments draining the Palaeogene Indo-Burman Ranges reveals a persistent youngest population of *c*. 37 Ma. This indicates that the depositional age and subsequent exhumation of the sediment extends to younger than *c*. 37 Ma. This gives tighter constraint on previous estimations of late Eocene–Oligocene age and exhumation of the Arakan Yoma (Indo-Burman Ranges) (Mitchell 1993), although we note that the youngest population of modern river sand need not be representative of its entire drainage basin and earlier exhumation of some rocks may well have occurred. To the west, as the succession youngs into the Neogene Chittagong Hill Tracts (as described below) the maximum age of deposition is constrained at younger than 6 Ma and probably reflects the diachronous exhumation history of the region.

The Neogene Indo-Burman Ranges. Fission-track data on detrital zircons from Neogene bedrock samples reveal a youngest age of 6 Ma in the westernmost sample, and from 13 to 29 Ma eastward towards the Palaeogene Indo-Burman Ranges as indicated by the ^{39}Ar–^{40}Ar white mica data. This indicates that the depositional age of the sediment furthest west in Myanmar was post 6 Ma to latest Miocene, but eastward to the border with the Palaeogene the maximum depositional age increases to post 29 Ma. These data are consistent with the westward younging of the whole sequence from the Palaeogene Indo-Burman Ranges to the west-vergent Chittagong Hill Tracts, and their equivalent along the Arakan coast.

Discussion and conclusions

Youngest zircon fission-track populations constrain the sampled Palaeogene deposits as post 37 Ma, with exhumation occurring thereafter (with older deposits also possibly occurring). In contrast, youngest zircon fission-track and U–Pb ages constrain the most western Neogene deposits at younger than 6 Ma. Westward younging of the youngest zircon fission-track population is consistent with progressive exhumation of the Indo-Burman Ranges from the Palaeogene in the east to the Neogene in westernmost Myanmar.

The Neogene rocks of the Indo-Burman Ranges show close affinity with signatures from the foreland basin Dumre Formation and Siwaliks, which record erosion from the Himalaya since the Miocene. As such, the Neogene Indo-Burman Ranges most probably represent accretionary prism sediments of the Himalayan-derived palaeo-Bengal Fan.

In contrast, the Palaeogene rocks of the Indo-Burman Ranges show clear evidence of significant arc-derived input. This is in contrast to the approximately coeval Himalayan-derived Bhainskati and Barail Formations of the foreland and remnant ocean basins. As there is no evidence of such substantial input of Transhimalayan (arc) detritus to any basins south of the eastern Himalaya during this period, we suggest that the source of this detritus in the Indo-Burman Ranges is the Burmese portion of the arc, to the east of the Indo-Burman Ranges. The source of the older crustal component in the Palaeogene Indo-Burman rocks is ambiguous and may represent erosion from the rising southern flanks of the Himalaya, or the Burmese terranes along the Burman margin into which the arc is intruded. If the continental source is Himalayan, then the palaeogeographical environment of deposition of the Indo-Burman Ranges sediments most probably involved mixing in the subduction trench, with Burmese arc detritus bypassing the forearc and outer arc high through a series of canyons, as seen, for example, in the Tonga trench (Draut & Clift 2006). If the Burman margin is the older source, then forearc deposition on the Asian plate is the more likely depositional setting, as suggested by Mitchell (1993).

The systematic difference between the Palaeogene and Neogene signatures of the Indo-Burman Ranges may be explained either by their potentially different palaeogeographical location as outlined above, or by onset of substantial erosion of the Himalayas in the Neogene that initiated a swamping of the arc signal. Regardless, it appears that there is evidence of major, substantial, erosion from the Himalaya in the Neogene. However, significant erosion of the Himalayan mountain range during the Palaeogene remains equivocal. Our data are therefore consistent with models of crustal deformation that favour insignificant early erosion (Beaumont *et al*. 2001, 2004; Replumaz & Tapponier 2003; Jamieson *et al*. 2004).

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