Tectonics, exhumation, and drainage evolution of the eastern Himalaya since 13 Ma from detrital geochemistry and thermochronology, Kameng River Section, Arunachal Pradesh

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ABSTRACT

The exhumation history of the central Himalaya is well documented, but lateral variations in exhumation remain poorly constrained. In this study, we identify sediment source areas and examine the late Neogene exhumation history of the eastern Himalaya from the synorogenic sedimentary record of its foreland basin. We present Nd and Hf isotopic data as well as apatite and zircon fission-track analyses from the Miocene–Pliocene Siwalik Group along the recently dated Kameng River section in Arunachal Pradesh, northeastern India. Our isotopic data show that Siwalik Group sediments deposited between 13–7 and <2.6 Ma in Arunachal Pradesh were mainly derived from Higher Himalayan source rocks. In contrast, sediments deposited between ca. 7 and 3 Ma have far less negative εNd and εHf values that require involvement of the Gangdese Batholith and Yarlung suture zone source areas via the Brahmaputra River system. Consequently, these sediments should also record incision of the Namche Barwa massif by this river. Source-area exhumation rates of Himalayan-derived sediments, determined from detrital zircon fission-track data, were on the order of 1.8 km/m.y. in the fastest-exhuming areas. These rates are very similar to those calculated for the central Himalaya and have been relatively constant since ca. 13 Ma. Our results do not support the hypothesis of a major change in exhumation rate linked to either local or regional climate change or to Shillong Plateau uplift during the Miocene, as reported elsewhere. The zircon fission-track data further suggest that exhumation of the Namche Barwa massif between 7 and 3 Ma was much slower than the ~10 km/m.y. rate recorded in the recent past. Detrital apatite fission-track data indicate deformation of the Siwaliks due to forward propagation of the frontal thrust since around 1 Ma.

INTRODUCTION

The Himalaya region has significantly influenced both global and regional climate (e.g., Raymo and Ruddiman, 1992; Molnar et al., 1993), as well as sediment flux to the Indian Ocean, since ca. 50 Ma (Métivier et al., 1999; Clift, 2006). While the evolution of this mountain belt is primarily driven by India-Asia convergence, several authors have suggested that its relief and erosion patterns have been strongly affected by the monsoon climate since the Miocene (e.g., Bookhagen and Burbank, 2006; Clift et al., 2008a, 2008b; Iaffaldano et al., 2011). Therefore, the Himalaya represents a unique natural laboratory where the interactions between tectonics, erosion, climate, and drainage evolution can be investigated. Combined geochemical provenance and detrital thermochronologic analyses of synorogenic sediments of different depositional ages allow the reconstruction of the tectonic and erosional history of the mountain belt by constraining source areas and exhumation rates through time.

The long-term exhumation history of the western and central Himalaya has been described using detrital mica 40Ar-39Ar, zircon fission-track (ZFT), and apatite fission-track (AFT) analyses (White et al., 2002; Bernet et al., 2006; Szulc et al., 2006; van der Beek et al., 2006; Najman et al., 2006; DeCelles et al., 2004; Bernet et al., 2006). The history of the western syn- taxis has similarly been constrained by detrital studies in the foreland basin (e.g., Cerveny et al., 1988; Najman et al., 2003). In contrast, very little is known about the evolution of the eastern Himalaya. Thermochronologic and geochemical data from the Bengal Fan imply relatively continuous erosion over time on the scale of the Ganges and Brahmaputra drainage systems (van der Beek et al., 2006; Galy et al., 2010). Detrital AFT and ZFT data from eastern Nepal (Chirouze et al., 2012a) and in situ AFT data from Bhutan (Grujic et al., 2006) hint at slower (0.5–1 km/m.y.) long-term erosion rates in the eastern Himalaya compared to the central Himalaya (1–2 km/m.y.). Several studies have suggested that rapid (5–10 km/m.y.) focused exhumation in both the western and eastern syntaxes of the Himalaya is driven by incision of the Indus and Yarlung–Brahmaputra Rivers, respectively, following the so-called “tectonic aneuryms” hypothesis (Zeitler et al., 2001; Ding et al., 2001; Koons et al., 2002; Booth et al., 2009; Enkelmann et al., 2011). However, temporal constraints on drainage network evolution and the onset of rapid exhumation are currently not sufficiently well known to fully constrain this model.

Here, we present detrital AFT and ZFT data as well as whole-rock Nd and Hf isotopic data from samples collected from Miocene–Quaternary foreland basin sediments along the Kameng section in Arunachal Pradesh, northeastern India (Fig. 1), which was recently dated by magnetostratigraphy (Chirouze et al., 2012b). The evolution has been determined from isotope geochemistry, detrital zircon U/Pb geochronology, as well as ZFT and U/Pb double dating of single grains (Robinson et al., 2001; Huyghe et al., 2001, 2005; DeCelles et al., 2004; Bernet et al., 2006). The history of the western syn- taxis has similarly been constrained by detrital studies in the foreland basin (e.g., Cerveny et al., 1988; Najman et al., 2003). In contrast, very little is known about the evolution of the eastern Himalaya. Thermochronologic and geochemical data from the Bengal Fan imply relatively continuous erosion over time on the scale of the Ganges and Brahmaputra drainage systems (van der Beek et al., 2006; Galy et al., 2010). Detrital AFT and ZFT data from eastern Nepal (Chirouze et al., 2012a) and in situ AFT data from Bhutan (Grujic et al., 2006) hint at slower (0.5–1 km/m.y.) long-term erosion rates in the eastern Himalaya compared to the central Himalaya (1–2 km/m.y.). Several studies have suggested that rapid (5–10 km/m.y.) focused exhumation in both the western and eastern syntaxes of the Himalaya is driven by incision of the Indus and Yarlung–Brahmaputra Rivers, respectively, following the so-called “tectonic aneuryms” hypothesis (Zeitler et al., 2001; Ding et al., 2001; Koons et al., 2002; Booth et al., 2009; Enkelmann et al., 2011). However, temporal constraints on drainage network evolution and the onset of rapid exhumation are currently not sufficiently well known to fully constrain this model.
thermochronologic data provide constraints on exhumation rates in the eastern Himalaya and the deformation of the Sub-Himalayan foreland basin. Nd isotopes are used as provenance indicators following previous studies in the Himalaya (France-Lanord et al., 1993; Huyghe et al., 2001, 2005; Robinson et al., 2001; Clift et al., 2008a; Galy et al., 2010; Najman et al., 2012), while Hf-isotope data are reported for the first time in this region. We demonstrate that the Hf-isotopic system is an excellent proxy with which to distinguish sediment source areas. In the future, it could be used combined with Nd isotopes or alone on zircon populations. At the regional scale, the data are combined to discuss different scenarios of the evolution of the Yarlung-Brahmaputra drainage system since the mid-Miocene.

GEOLOGY OF THE EASTERN HIMALAYA

Plate reconstructions and geologic data indicate that collision between the Indian and Asian continents began during the early Eocene (Yin and Harrison, 2000; Zhu et al., 2005; Dupont-Nivet et al., 2010). This collision caused significant crustal shortening and thickening, resulting in the formation of the Tibetan Plateau and the Himalayan mountain belt (Hodges, 2000; Yin and Harrison, 2000). The Himalaya is classically subdivided into five lithotectonic zones (Fig. 1) separated by north-dipping crustal-scale faults (Le Fort, 1975; Yin and Harrison, 2000). From north to south, these are (1) the Indus-Yarlung suture zone, containing ophiolites of the Neotethys ocean and the Cretaceous–Tertiary Gangdese Batholith (also known as the Trans-Himalayan batholith) lying adjacent to the suture zone; (2) the Tethyan Himalaya Series, containing the Upper Proterozoic to Eocene sedimentary cover of the northern Indian margin; (3) the Higher (or Greater) Himalaya Series, composed of medium- to high-grade metamorphic crystalline rocks; (4) the Lesser Himalaya Series, mainly composed of low-grade Proterozoic metasedimentary rocks of the Indian plate as well as late Paleozoic–Mesozoic and Paleogene sedimentary rocks; and (5) the Sub-Himalaya, containing Neogene detrital sedimentary rocks of the Siwalik Group, derived from erosion of the orogen and incorporated into the propagating thrust wedge since the Pliocene. The Tethyan

Figure 1. Regional tectonic map showing simplified geology and the locations of major rivers (after Yin et al., 2006, 2010; Guillot and Charlet, 2007). The star indicates the location of the Kameng section. Tectonic structures: Indus-Yarlung suture zone (IYSZ), Main Frontal thrust (MFT), Main Boundary thrust (MBT), Main Central thrust (MCT), South Tibetan detachment (STD), Dauki fault (DF), Assam-Arakan thrust belt (AATB), and Tipi Thrust (TT).
Modern Drainage System of the Eastern Himalaya

The Yarlung-Brahmaputra River system, one of the major rivers of Asia, changes names twice along its 2900 km course from SW Tibet, across the eastern Himalayan syntaxis and into the Bay of Bengal (Fig. 1). In Tibet, where it flows along the Indus-Yarlung suture zone and into the Namche Barwa massif, it is known as the Yarlung River (Yarlung Tsangpo). Downstream of the Namche Barwa massif, it is called the Siang River, and it becomes the Brahmaputra River in the Himalayan foreland basin (Fig. 1). It is debated when and how the Yarlung-Brahmaputra River began to incise the eastern Himalayan syntaxis. Some authors (e.g., Seeer and Gornitz, 1983; Brookfield, 1998; Clark et al., 2004) argue for a paleo-Yarlung River that flowed further to the east than today, into either the present-day Red or Irrawaddy Rivers. Such a drainage network implies that the Yarlung River was captured by the Siang River after ca. 10 Ma (Brookfield, 1998) but before ca. 4 Ma (Zeitler et al., 2001; Clark et al., 2004). Others, however, have argued for long-term stability in the drainage patterns of the southeastern Tibetan Plateau (e.g., Burg et al., 1998; Hallet and Molnar, 2001), and sediment provenance data from the Bengal Fan suggest that the Yarlung-Brahmaputra drainage system has remained stable and flowed into the Bengal Fan since the mid-Miocene (Galy et al., 2010).

Rapid erosion in the Namche Barwa massif currently provides between 46% and 60% of the sediment carried by the Siang River downstream of the Yarlung Gorge (Singh and France-Lanord, 2002; Stewart et al., 2008; Enkelmann et al., 2011). The isotopic signature of modern Brahmaputra sediment along the Assam Plain is dominated by the input from the Namche Barwa syntaxis, with only minor contributions from Himalayan tributaries (Singh and France-Lanord, 2002). Using heavy-mineral and detrital zircon U/Pb analyses, Garzanti et al. (2004) and Cina et al. (2009) showed that the Namche Barwa contribution still represents ~40% of the Brahmaputra sediment flux upstream of its confluence with the Ganges River.

Eastern Syntaxis

The eastern Himalayan syntaxis is the termination of the Himalayan arc, where the structural trend gradually changes from E-W, as observed in southeastern Tibet and the Himalayan orogen, to N-S (Fig. 1). Embedded in the syntaxis, there is an active antiformal metamorphic structure called the Namche Barwa–Gyala Peri massif. Around this structure, and separated from it by a mylonitic shear zone, lies the Gangdese or Trans-Himalayan plutonic belt of the southern Lhasa terrane. The Siang River crosses the orogen east of the Namche Barwa, exposing high-grade metamorphic rocks and very young (<10 Ma) granitic intrusions (Burg et al., 1998; Ding et al., 2001; Zeitler et al., 2001; Booth et al., 2004, 2009). The 40Ar/39Ar white mica, AFT, ZFT, and (U-Th)/He ages indicate that the Namche Barwa massif has been exhumed extremely rapidly (up to 10 km/m.y.) over at least the past 5 m.y. (Burg et al., 1998; Finnegan et al., 2008; Stewart et al., 2008). Such rapid exhumation has been attributed to intense incision by the Yarlung River, coeval with crustal-scale folding (Burg et al., 1998), and possibly facilitated by local feedbacks between tectonic and surface processes (Zeitler et al., 2001; Finnegan et al., 2008).

Shillong Plateau

Another important element of the eastern Himalayan framework is the Shillong Plateau (Fig. 1), which is considered to be a basement pop-up structure uplifted along steep and seismically active crustal-scale reverse faults (Billham and England, 2001; Rajendran et al., 2004; Biswas and Grasemann, 2005; Kayal et al., 2006). These faults cause a 5 km offset of the Moho below the plateau (Mitra et al., 2005) and, therefore, do not seem to be connected to the Himalayan system of crustal-scale thrusts. Apatite (U-Th)/He data suggest that exhumation of the Shillong Plateau initiated 8–15 Ma, but surface uplift may only have started when the resistant basement rocks were exposed by erosion from underneath the easily erodible sedimentary cover, possibly as late as 3–4 Ma (Biswas et al., 2007; Clark and Billham, 2008). Current convergence rates across the eastern Himalaya, estimated from global positioning system (GPS) measurements (Mukul et al., 1010), are 15–20 mm/yr, within error of the 18 ± 3 mm/yr convergence rate observed in the central Himalaya (Bilham et al., 1997; Larson et al., 1999; Jouanne et al., 2004). Approximately 1.5–3.5 mm/yr (~10%–20%) of the present-day N-S convergence in the eastern Himalaya may be accommodated by the Shillong Plateau (Biswas et al., 2007; Mukul et al., 2010).

STRATIGRAPHY OF THE SIWALK GROUP ALONG THE KAMENG SECTION

The Neogene foreland basin deposits in Arunachal Pradesh are subdivided into the Dafila, Subansiri, and Kimin Formations, based on sedimentary facies associations (Karunakaran and Rao, 1976; Kumar, 1997). These formations have been correlated with the lower, middle, and upper Siwalik Group, respectively, of the western and central parts of the Himalayan foreland basin (Yin, 2006). The ~6-km-thick Kameng section, which constitutes a complete Siwalik Group succession exposed along the Kameng River, was recently logged and magnetostatigraphically dated (Fig. 2; Chirouze et al., 2012b).

The Dafila Formation (equivalent to the lower Siwalik Group; Fig. 2) is composed of 1–5-m-thick fine-grained sandstone beds, alternating with up to 50-cm-thick drab-colored siltstone layers. Within mudstone/siltstone beds, wave ripples, leaf impressions, and burrows are common. Well-developed paleosol horizons are common. This type of deposit may be attributed to high-sinuosity streams, possibly in a low-gradient marine or lacustrine delta-plain setting (Chirouze et al., 2012b). The age of the exposed part of the Dafila Formation along the Kameng section is constrained to be between ca. 10.5 and ca. 13 Ma (chrons C5n.2n to C5Ar.1n; Chirouze et al., 2012b).

The Subansiri Formation (middle Siwalik Group; Fig. 2) presents medium- to coarse-grained thick-bedded yellowish sandstone. Bed thickness ranges from 2 m in the lower part of the formation to 30 m in its upper part. Amalgamated sheet sandstone bodies and large-scale cross-bedding are common features, and the base of the beds is occasionally marked with pebbly conglomerate units. Paleocurrent directions in the Kameng section are highly variable, ranging from N120° to N270° in the lower part of the formation (Fig. 2), with a mean direction to the southwest. Such a facies may be attributed to a large sandy braided-river system. The age of the Subansiri Formation along the Kameng section is between ca. 10.5 and ca. 2.6 Ma (Chirouze et al., 2012b).

The Kimin Formation (upper Siwalik Group; Fig. 2) is characterized by coarse sand and conglomerate deposits interlayered with well-
developed silt layers, and can be attributed to a gravelly braided-river system. The magnetostratigraphy, together with detrital AFT data, implies that the Kimin Formation is younger than ca. 2.6 Ma (chron C2An.1n; Chirouze et al., 2012b).

To the south, the Siwalik Group is separated from the Quaternary deposits of the Brahmaputra floodplain by the Main Boundary thrust, while to the north, it is separated from the Lesser Himalaya Series by the Main Frontal thrust (e.g., Yin et al., 2010). Within the Kameng section, the Tipi thrust places the Dafla Formation over the Kimin Formation (Fig. 2), such that the younger part of the section (upper Subansiri Formation and Kimin Formation) is exposed in the footwall of the thrust, while the older part (Dafla Formation and lower part of the Subansiri Formation) crops out in its hanging wall (Fig. 2).

**METHODS**

**Geochemical Analyses**

Sixteen samples were collected along the Kameng River section (Fig. 2) for Nd and Hf isotopic analyses as well as for trace-element contents. Medium-grained sandstone with little mud matrix was carefully selected from homogeneous layers to avoid variations in trace-element contents as would be created by variable amounts of carbonates or heavy minerals. Selection of such samples does not create any bias for Nd isotopes because most minerals share similar Sm/Nd ratios (Garçon et al., 2011a, 2011b). In contrast, selection of relatively coarse-grained sediments is crucial for Hf isotopic analyses because the source-rock Hf signature is best represented by Hf contained in zircon (Garçon et al., 2011a). Part of the source-area database for Nd isotopes in the eastern Himalaya comes from modern river sands (Singh and France-Lanord, 2002) and is therefore most readily compared to sandstone samples. In addition, two sand samples were collected from the modern Kameng and Brahmaputra Rivers (upstream of the Kameng confluence).

Whole-rock trace-element concentrations and Nd and Hf isotopic compositions were obtained using liquid aliquots of a single-acid dissolution of rock powder in Parr bombs. Trace-element determinations as well as Nd and Hf separations were performed in the geochemistry laboratory at the Institut des Sciences de la Terre, Grenoble, France. Both trace-element and isotopic compositions were measured using the technique described in Chauvel et al. (2011). Reproducibility of the rare earth elements (REEs) analyses is excellent and was controlled with complete...
duplicate samples (see GSA Data Repository Table DR1). Isotopic compositions were measured on a Nu Plasma HR multicollector inductively coupled plasma–mass spectrometer (MC-ICP-MS) at Ecole Nationale Supérieure Lyon, France. The Ames-Rennes Nd standard gave an average $^{144\text{Nd}}/^{144\text{Nd}}$ ratio of 0.511967 ± 7 (2σ, 18 runs), and ratios provided in Table 1 were corrected to the preferred value of 0.511960 published by Chauvel and Blichert-Toft (2001). The average $^{176\text{Hf}}/^{177\text{Hf}}$ ratio of the JMC age standards were corrected to the preferred value of 0.511960 ± 7 (2σ, 8 runs), and all listed ratios were corrected for the reference value of 0.512160 as published by Vervoort and Blichert-Toft (1999). Blanks were lower than 50 pg for both Nd and Hf; their contributions were negligible relative to the amount of element analyzed. Complete duplicate analyses were performed and the results showed that the measurements could be reproduced within analytical errors (±0.5 εNd and ±εHf; see Table 1 for the definition of ε).

**Fission-Track Analysis of Detrital Apatite and Zircon**

Apatite and zircon grains were separated from a dozen sandstone samples from the Kameng section (Fig. 2; Tables 2 and 3) using standard heavy-liquid and magnetic separation techniques. Apatite aliquots were mounted in epoxy, polished to expose internal crystal surfaces, and etched with 5.5 M HNO3 for 20 s at 21 °C. Zircons were mounted in Teflon® sheets, polished, and etched at 228 °C in a eutectic NaOH-KOH melt. Two mounts per sample were assembled and etched between 5 and 40 h. The etching progress and the quality of the etched tracks were controlled between subsequent etching steps to obtain countable fission tracks for the majority of the grains (Bernet et al., 2004).

All samples were covered with muscovite sheets as external detectors and sent for neutron irradiation to the FRM II Research Reactor at the Technische Universität München, Germany. Apatite samples were irradiated together with IRMM 540R glass standards and Durango and Fish Canyon Tuff age standards. Zircon samples were irradiated together with CN1 glass standards and Fish Canyon Tuff and Buluk Tuff age standards. After irradiation, the muscovite sheets of all samples and standards were etched for 18 min at 21 °C in 48% HF. The samples and standards were counted dry at 1250× magnification, using an Olympus BH2 optical microscope. The objective was to date up to 100 grains per sample, if possible.

Observed grain-age distributions were decomposed into major grain-age components or peaks using a binomial peak-fitting procedure (Stewart and Brandon, 2004). To determine maximum exhumation rates, lag times (defined as the difference between the peak age and the depositional age; e.g., Garver et al., 1999) were calculated for the youngest ZFT age peak in each sample. First-order estimates of exhumation rate were determined using a one-dimensional steady-state thermal model (Brandon et al., 1998; Reiners and Brandon, 2006). The ZFT closure temperature was estimated following Dodson’s (1973) approach and using kinetic parameters estimated by Brandon et al. (1998). Other parameter values used in the model were: surface temperature $T_s = 20 °C$; initial geothermal gradient $G = 20 °C/km$; model thickness $L = 25 km$; and thermal diffusivity $κ = 25 km^2/m.y$. Uncertainties in predicted exhumation rates are propagated from 2σ uncertainties in ZFT peak ages.

**RESULTS**

**Trace-element and Isotope Geochemistry**

Trace-element concentrations are given in GSA Data Repository Table DR1 (see footnote 1), while the Nd and Hf isotopic ratios are presented in Table 1. The trace-element patterns of the samples from the Kameng section are remarkably uniform and similar to average upper continental crust (Fig. DR1 [see footnote 1]). The only significant difference is the systematic and large negative Sr anomaly present in all samples, which is explained by the low proportion of carbonates present in these sediments (Taylor and McLennan, 1985). The two modern sediment samples collected in the Brahmaputra and Kameng Rivers are generally similar to other samples, but they are systematically richer in rare earth and high field strength elements. This enrichment is most probably caused by the high proportion of heavy minerals in these modern samples, which were collected from riverbanks where heavy minerals may have been concentrated hydrodynamically.

The $\varepsilon_{\text{Nd}}$ values for samples from the Kameng section range from –12.4 to –12.1, respectively, for the Kameng River and –12.4 and –12.1, respectively, for the Brahmaputra River (Fig. 3).

When plotted as a function of stratigraphic depth along the Kameng section (Fig. 4), significant changes in $\varepsilon_{\text{Nd}}$ values are observed, and the variability is much larger than that reported from the central Himalaya (Huyghe et al., 2001, 2005; Robinson et al., 2001). However, the range of $\varepsilon_{\text{Nd}}$ values that we measured is in agreement with previously published values of eastern Himalayan tributaries ($\varepsilon_{\text{Nd}}$; –21 to –12; Singh and France-Lanord, 2002) and the Brahmaputra River ($\varepsilon_{\text{Nd}}$; –17 to –7; Singh and France-Lanord, 2002). The evolution through time of the bulk-rock $\varepsilon_{\text{Nd}}$ values along the Kameng section suggests three main periods (Fig. 4). Seven samples from the Dafila Formation, dated between 13 Ma and 8.2 Ma, have $\varepsilon_{\text{Nd}}$ values around –16.5, a value that is very similar to that of the modern Kameng River sand. Samples dated between 7.3 and 3.1 Ma have less negative $\varepsilon_{\text{Nd}}$ values around –12.5, a value similar to the modern Brahmaputra River sand; in contrast, the two youngest samples (KAM 8 and KAM 14, dated at 0.9 and 2 Ma, respectively) have more negative $\varepsilon_{\text{Nd}}$ values, which are again similar to the modern Kameng River sediment. Samples with high $\varepsilon_{\text{Nd}}$ values, similar to that of the Brahmaputra River sand, also have less negative $\varepsilon_{\text{Nd}}$ values at about –16, while samples with low $\varepsilon_{\text{Nd}}$ values, similar to that of the Kameng River sand, have much more negative $\varepsilon_{\text{Nd}}$ values around –22. The difference between the two groups is larger for Hf isotopes (~6 ε units) than for Nd isotopes (~4 ε units), as shown in Figure 3, where $\varepsilon_{\text{Nd}}$ and $\varepsilon_{\text{Hf}}$ data are plotted and compared to Himalayan source-rock data published by Chu et al. (2011).

Apatite Fission-Track Results

Ten samples collected along the Kameng section were dated with the AFT method. All ten samples failed the $χ^2$ test, indicating the presence of several age components in each sample. The central age and component age peaks for each sample are presented in Table 2. The overall grain-age distributions and binomial best-fit peaks for each sample are shown in Figure DR2 (see footnote 1). Only the samples with depositional ages ≤ 4 Ma, collected from the footwall of the Tipi thrust, have central and peak ages older than the depositional age. Stratigraphically older samples, from the hanging wall of the Tipi thrust, have central ages and/or significant age peaks that are younger than the depositional age. The exception is sample KAM5, which has a central age and peak age older than its depositional age of ca. 6.3 Ma (Table 2). The variation of central AFT ages versus stratigraphic depth is shown in Figure 5.
Chirouze et al. (2012b) were counted at 1250× dry (100× objective, 1.25 tube factor, 10× oculars) by F. Chirouze using an IRMM540R zeta of 272.00 ± 7.80 (±1 SE). Depositional ages are after KAM 16 and binomial best-fit peaks for each sample are components. The overall grain-age distributions of twelve samples have three age populations shown in Figure DR3 (see footnote 1). Five out of twelve samples have three age populations and three samples have four populations, while four samples have only two age populations; all binomial-fitted age peaks are older than the depositional age of the samples (Table 3). Over-all, the peak ages of the 12 samples can be divided into three main groups. The oldest group (P3) has peak ages between 200 and 100 Ma.

The middle age group (P2) has peak ages of ca. 25–16 Ma, while the youngest age group (P1) decreases systematically in age up section, with peak ages ranging from 14 to 4 Ma (Fig. 6). Maximum source-area exhumation rates, determined from P1 lag times using a one-dimensional (1-D) steady-state thermal model, are on average 1.8 ± 0.9 km/m.y. (Fig. 7).

DISCUSSION

Provenance Analysis

Nd isotopes have been widely used for provenance studies of sediments, but this is not the case for Hf isotopes. Here we present the first study evaluating their potential as a source-area indicator in continental deposits. Nd and Hf isotopic ratios of samples from the Kameng section are correlated, and the variation plots on the mantle array of Chauvel et al. (2008) within the field of crustal material (Vervoort and Blichert-Toft, 1999) (Fig. 3), suggesting that the two isotopic compositions are characteristic of the source material and were not biased by selective heavy mineral storage upstream in the paleoriver system. If the analyzed sediments were lacking monazite and zircon present in the source granitoids, they would have trace-element patterns different from that of upper continental crust (see GSA Data Repository Table DR1 [see footnote 1]), and their Hf isotopic compositions would be displaced to elevated Hf isotopes relative to their Nd isotopic compositions in Figure 3, as is the case for Hf isotopes. Here we present the first study evaluating their potential as a source-area

TABLE 1. Nd AND Hf ISOTOPIC COMPOSITIONS MEASURED AT THE KAMENG SECTION AND RIVER SEDIMENTS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age (Ma)</th>
<th>143Nd/144Nd</th>
<th>εNd</th>
<th>P1</th>
<th>176Hf/177Hf</th>
<th>εHf</th>
<th>P2</th>
<th>176Hf/177Hf</th>
<th>εHf</th>
<th>P3</th>
<th>176Hf/177Hf</th>
<th>εHf</th>
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<tr>
<td>Brahmaputra River</td>
<td>0</td>
<td>0.511999</td>
<td>–2</td>
<td>0.282442</td>
<td>0.000007</td>
<td>-12</td>
<td>–12</td>
<td>0.282236</td>
<td>-19.4</td>
<td>–12</td>
<td>0.282236</td>
<td>-19.4</td>
</tr>
</tbody>
</table>

Note: The εNd and εHf values were calculated relative to the bulk earth values published by Bouvier et al. (2008): (143Nd/144Nd)BSE = 0.512630 and (176Hf/177Hf)BSE = 0.282785 and using the following definitions: εNd = ([143Nd/144Nd]sample/[143Nd/144Nd]BSE – 1) × 10,000. No age correction was performed because the ages of sediments are sufficiently young for the correction to be negligible. Dup. stands for complete duplicate analysis.

TABLE 2. DETRITAL APATITE FISSION-TRACK RESULTS FOR THE KAMENG SECTION

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depositional age (Ma)</th>
<th>N</th>
<th>Age range (Ma)</th>
<th>P1 (Ma)</th>
<th>εNd</th>
<th>P2 (Ma)</th>
<th>εNd</th>
<th>P3 (Ma)</th>
<th>εNd</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAM 20</td>
<td>0</td>
<td>53</td>
<td>0.4–44.9</td>
<td>2.9 ± 0.8</td>
<td>14.6 ± 10.3</td>
<td>–</td>
<td>3.6 ± 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 30</td>
<td>0</td>
<td>50</td>
<td>0.4–18.1</td>
<td>1.3 ± 1.8</td>
<td>7.3 ± 2.0</td>
<td>–</td>
<td>5.0 ± 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 8</td>
<td>0.9</td>
<td>71</td>
<td>0.9–48.8</td>
<td>47.4%</td>
<td>52.6%</td>
<td>–</td>
<td>5.9 ± 0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 14</td>
<td>2</td>
<td>58</td>
<td>0.7–28.8</td>
<td>85.5%</td>
<td>14.5%</td>
<td>–</td>
<td>5.1 ± 0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 7</td>
<td>4</td>
<td>70</td>
<td>0.9–99.0</td>
<td>31.1 ± 1.1</td>
<td>71.2 ± 2.4</td>
<td>66.9 ± 65.5</td>
<td>4.6 ± 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 15</td>
<td>5.5</td>
<td>90</td>
<td>0.9–28.7</td>
<td>40.4%</td>
<td>13.6 ± 7.7</td>
<td>–</td>
<td>5.9 ± 0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 5</td>
<td>6.3</td>
<td>55</td>
<td>1.7–53.7</td>
<td>37.1%</td>
<td>13.9 ± 4.7</td>
<td>35.9 ± 19.5</td>
<td>10.9 ± 1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 12</td>
<td>8.8</td>
<td>33</td>
<td>0.5–21.5</td>
<td>52.9%</td>
<td>40.4%</td>
<td>6.7%</td>
<td>2.6 ± 0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 11</td>
<td>10.6</td>
<td>53</td>
<td>0.5–25.6</td>
<td>0.6 ± 0.8</td>
<td>2.5 ± 1.0</td>
<td>6.9 ± 2.4</td>
<td>2.6 ± 0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAM 16</td>
<td>13.1</td>
<td>62</td>
<td>0.4–188.6</td>
<td>2.2 ± 0.6</td>
<td>14.3 ± 6.6</td>
<td>69.8 ± 54.5</td>
<td>3.7 ± 0.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: N is the total number of grains counted; binomial peak-ages are given ±2 standard error (SE). The percentage of grains in a specific peak is also given. All samples were counted at 1250× dry (100× objective, 1.25 tube factor, 10× oculars) by F. Chirouze using an IRMM540R zeta of 272.00 ± 7.80 (±1 SE). Depositional ages are after Chirouze et al. (2012b).
case with oceanic clays (Vervoort et al., 1999; Carpentier et al., 2009; Garçon et al., 2011b). In that case, the measured εNd would be representative of the source areas, but the measured εHf could not be used to identify the relative contributions of different sources for each sample (Garçon et al., 2011a, 2011b). This is not the case with our data because they lie on the mantle array; their Hf isotopes are therefore representative of the source materials.

Unfortunately, hardly any Hf isotopic analyses have currently been performed on the Himalayan source rocks, and our combined Nd-Hf data can only be compared to few published compositions of the source areas. Recently, Chu et al. (2011) reported Nd and Hf isotopic data measured on material sampled along the Indus-Yarlung Suture Zone, an area that mainly consists of oceanic crust forming the Gangdese batholith. Erosion of these rocks with positive εNd and εHf values contributes to the sedimentary load of the Brahmaputra River and explains why the present Brahmmaputra sand has higher εNd and εHf than the present-day Kameng River sand (Fig. 3). Most samples from the Kameng section, including the modern Kameng sample, have εHf values ranging between −26 and −19, a range that can be considered as characteristic of the sources located upstream of the modern Kameng in the Higher Himalaya Series because their εNd values coincide with the usual High Himalaya field. In summary, our combined εNd-εHf study demonstrates the potential of Hf isotopes to decipher the provenance of sediment samples. This isotopic system can either be used combined with the more classical Nd isotopic approach or alone using zircons, because Hf is almost exclusively hosted by zircons (Garçon et al., 2011a), and their Hf isotopic analysis is relatively simple to acquire using laser-ablation techniques coupled to multicollector ICP-MS.

Although the number of Nd isotopic analyses available is much larger than that of Hf analyses, the Nd isotopic compositions of the various lithotectonic units exposed in the eastern Himalaya are not fully constrained. They can be summarized as follows:

(1) The Higher Himalayan Series in the Namche Barwa massif and the Kameng drainage area is characterized by εNd values ranging from −12 to −19 (Singh and France-Lanord, 2002, and references therein), while the Lesser

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depositional age (Ma)</th>
<th>N</th>
<th>Age range (Ma)</th>
<th>εNd</th>
<th>εHf</th>
<th>Other peaks (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAM 20</td>
<td>0</td>
<td>100</td>
<td>1.7–228</td>
<td>3.9 ± 0.7</td>
<td>18.9 ± 1.9</td>
<td>115.8 ± 32.5</td>
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<tr>
<td>KAM 30</td>
<td>5</td>
<td>100</td>
<td>2.6–272</td>
<td>6.4 ± 0.6</td>
<td>17.4 ± 1.8</td>
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<tr>
<td>KAM 14</td>
<td>5.5</td>
<td>101</td>
<td>2.5–393</td>
<td>6.5 ± 1.1</td>
<td>16.4 ± 21.9</td>
<td>158.9 ± 24.8</td>
</tr>
<tr>
<td>KAM 3</td>
<td>3</td>
<td>48</td>
<td>7.8–196</td>
<td>8.1 ± 1.9</td>
<td>22.4 ± 3.5</td>
<td>123.4 ± 48.5</td>
</tr>
<tr>
<td>KAM 15</td>
<td>4.5</td>
<td>53</td>
<td>4.7–245</td>
<td>8.6 ± 1.2</td>
<td>23.9 ± 2.3</td>
<td>117.8 ± 43.4</td>
</tr>
<tr>
<td>KAM 4</td>
<td>3.8</td>
<td>45</td>
<td>7.8–312</td>
<td>9.5 ± 1.1</td>
<td>16.3 ± 3.8</td>
<td>108.0 ± 14.9</td>
</tr>
<tr>
<td>KAM 3</td>
<td>3.8</td>
<td>97</td>
<td>7.8–271</td>
<td>14.1 ± 2.4</td>
<td>20.6 ± 3.8</td>
<td>155.0 ± 14.9</td>
</tr>
<tr>
<td>KAM 11</td>
<td>10.6</td>
<td>100</td>
<td>7.8–332</td>
<td>12.5 ± 1.4</td>
<td>20.5 ± 3.2</td>
<td>188.7 ± 33.5</td>
</tr>
<tr>
<td>KAM 5</td>
<td>2.9</td>
<td>50</td>
<td>4.8–233</td>
<td>8.2 ± 1.2</td>
<td>20.1 ± 2.5</td>
<td>135.1 ± 58.2</td>
</tr>
<tr>
<td>KAM 9</td>
<td>2.7</td>
<td>59</td>
<td>20.7–403</td>
<td>13.5 ± 1.1</td>
<td>20.7 ± 6.5</td>
<td>189.4 ± 20.5</td>
</tr>
<tr>
<td>KAM 6</td>
<td>2.1</td>
<td>87</td>
<td>8.4–400</td>
<td>16.3 ± 1.4</td>
<td>17.0 ± 1.7</td>
<td>153.1 ± 21.5</td>
</tr>
</tbody>
</table>

Note: N is the total number of grains counted; binomial peak-ages are given ±2 standard error (SE). The percentage of grains in a specific peak is also given. All samples were counted at 1250x dry (100× objective, 1.25 tube factor, 10× oculars) by M. Bernet using a CN1 zeta of 178.55 ± 5.10 (±1 SE). Depositional ages are after Chirouze et al. (2009; Garçon et al., 2011a).
Himalaya Series in Bhutan, to the west of Arunachal Pradesh, has εNd between −21.4 and −19.4 (McQuarrie et al., 2008). These data suggest that both the Higher and Lesser Himalaya Series in the eastern part of the belt have Nd isotopic compositions comparable to those of the western and central Himalaya (France-Lanord et al., 1993; Ahmad et al., 2000, and references therein; Robinson et al., 2001, and references therein; Richards et al., 2005). The εNd values reported for the Transhimalayan plutonic rocks of the Gangdese Batholith belt are much less negative, between −6 and −8 (Singh and France-Lanord, 2002, and references therein; Chu et al., 2011).

(2) Compared to the geological units, the isotopic compositions of sands collected in modern rivers are much better documented (Pierson-Wickmann et al., 2000; Singh and France-Lanord, 2002); significant differences exist between the sand carried by the eastern Himalayan tributaries, which are transverse rivers that drain only the Indian plate (50% of the εNd values range from −16.8 to −13.8) and the Brahmaputra River (50% of the εNd values range from −14 to −13). These ranges are shown by boxes in Figure 4. Our new measurements on modern sediments collected in the Kameng and Brahmaputra Rivers are entirely consistent with the existing data. The less negative εNd values observed in the Brahmaputra River sediments are attributed to the erosion of terrains with elevated εNd values, which are present only in the Indus-Yarlung suture zone and the Indo-Burman Ranges (Singh and France-Lanord, 2002). Based on these constraints, the changes in εNd values through time, as measured in the Kameng section (Fig. 4), can be used to trace the evolution of the regional drainage system.

Between 13 Ma and 7 Ma, εNd values measured in the Kameng section samples (−17.1 to −15.8) are similar to values reported for sands from the modern eastern Himalayan tributaries and the Kameng River (Fig. 4). These values are also similar to values reported for Neogene sedimentary rocks produced by erosion of Higher Himalayan source rocks in the central Himalaya (−15 to −19) (Huyghe et al., 2001, 2005; Robinson et al., 2001). While it could be argued that the Kameng sediments partly originated from the sedimentary cover of the Shillong Plateau (which is composed essentially of recycled Himalayan material), paleocurrent measurements in the Dafla and lower Subansiri Formations rule out northward sediment transport required by such a scenario (Fig. 2; Cina et al., 2009). Moreover, this scenario is not compatible with our ZFT results, since zircons derived from the Shillong Plateau do not show age peaks <100 Ma; the main ZFT age peaks in

![Figure 4. εNd variation along the Kameng section compared to central Himalayan data from Huyghe et al. (2001, 2005) and Robinson et al. (2001). Modern river-sediment values for the Brahmaputra, the Siang, and the eastern Himalayan tributaries are from Singh and France Lanord (2002), and modern value for the Yarlung is from Pierson-Wickmann et al. (2000). Presence or absence of Gangdese Batholith (GB) zircon U/Pb ages (as reported by Cina et al., 2009) is also indicated. All εNd values were recalculated using the new Bulk Silicate Earth (BSE) values of Bouvier et al. (2008).](http://gsabulletin.gsapubs.org)
these sediments are between 300 and 500 Ma (Najman et al., 2008). Sample KAM 12, dated at ca. 9 Ma, has a less negative $\varepsilon_{\text{Nd}}$ value at $-14$ (Fig. 4), which could be attributed to the input of sediments coming from a source with a less negative Nd isotopic signature. However, this value is still within the range observed in the eastern Himalayan tributaries (Singh and France-Lanord, 2002). In addition, we did not observe a change in sedimentary facies and paleocurrent directions at this level of the section and therefore have no indication that a major change in the drainage system occurred at that time.

The $\varepsilon_{\text{Nd}}$ values in samples from the upper part of the Subansiri Formation, deposited between ca. 7 and 3 Ma, are less negative ($-12.4$ to $-13.8$) and differ significantly from values measured in the central Himalayan Siwaliks (Fig. 4). These less negative $\varepsilon_{\text{Nd}}$ values can only be explained by input of material from the Indus-Yarlung suture zone, which is currently drained by the Yarlung-Brahmaputra River. The $\varepsilon_{\text{Nd}}$ values of these sediments are similar to the average isotopic compositions reported for modern Brahmaputra and Siang River sediments (Fig. 4), which are dominated by sediment input from the Namche Barwa massif (Singh and France-Lanord, 2002). Our isotope geochemistry data are consistent with zircon U-Pb ages from the Subansiri Formation in the Kameng and Subansiri sections reported by Cina et al. (2009), which also imply input of Gangdese arc material. Therefore, the combined data strongly suggest that the river that carried sediments to be deposited in the Kameng area at that time drained the Indus-Yarlung suture zone, which implies either that these sediments were deposited by a paleo–Brahmaputra River already connected to the Indus-Yarlung suture zone, or that the Kameng (or adjacent Subansiri) catchment was much larger and connected to the Indus-Yarlung suture zone. Both scenarios are consistent with the sedimentological evidence for a large river system at this time (Fig. 2; Chirouze et al., 2012b). Although paleocurrent directions could potentially discriminate between these scenarios, we lack a sufficient number of paleocurrent measurements from the 7–3.5 Ma sandstones of the section because of the coarse-grained and massive nature of these sandstones and the limited accessibility of the outcrops (by raft only). We will discuss the implications for drainage development in more detail in the next section.

The $\varepsilon_{\text{Hf}}$ values of our samples are in good agreement with the provenance analysis based on $\varepsilon_{\text{Nd}}$. Lacking Hf isotope data for Himalayan source rocks (i.e., Tethyan Himalaya Series, Higher Himalaya Series, and Lesser Himalaya Series), the modern Kameng River sample, with its $\varepsilon_{\text{Hf}}$ value of $-19.4$, can be used as an average for the Higher Himalaya and Lesser Himalaya composition. The Kameng River only drains these source rocks, and its $\varepsilon_{\text{Hf}}$ value is significantly different from that of the modern Brahmaputra River. Future acquisition of

Figure 5. Plot of apatite fission-track (AFT) central age vs. stratigraphic depth for the hanging wall and footwall of the Tipi thrust, and schematic reconstruction of the thrusting sequence within the Kameng section: (A) prior to activation of the Tipi thrust at ca. 1 Ma; (B) prior to activation of the Main Frontal thrust <1 Ma; and (C) present-day situation. Partially reset samples show central ages close to or younger than the depositional age. MBT—Main Boundary thrust, TT—Tipi thrust, MFT—Main Frontal thrust. Black squares indicate the position of reset AFT samples. The present-day position of the frontal thrust is from Yin et al. (2010).
Figure 6. Lag-time plot of zircon fission-track (ZFT) age peaks of the Kameng section. Thick black line—young (P1) moving age peak; light-gray band—intermediate (P2) static age peak; darker-gray band—old (P3) static age peak. Thin continuous lines indicate constant lag times at 4 m.y. intervals.

Hf isotopic compositions of both granitoids and sediments produced by erosion of the mountain range could provide interesting additional constraints to decipher the erosional history of Himalayan rocks.

**Drainage Evolution**

The geochemical provenance information presented in this study implies reorganization of the drainage system in the eastern Himalayan during the late Miocene–Pliocene. Prior to ca. 7 Ma, the $\varepsilon_{\text{Nd}}$ signal indicates that sediments of the Kameng section were derived from eastern Himalayan sources (Tethyan Himalaya Series, Higher Himalaya Series, and Lesser Himalaya Series). Starting at ca. 7 Ma and up to ca. 3 Ma, less negative $\varepsilon_{\text{Nd}}$ values indicate the deposition of sediments with an $\varepsilon_{\text{Nd}}$ signature indicative of Indus-Yarlung suture zone source rocks, consistent with zircon U-Pb ages (Cina et al., 2009). Sediments deposited after 3 Ma in the Kameng section again originate solely from Himalayan source rocks. At present, Indus-Yarlung suture zone material is carried by the Yarlung-Siang-Brahmaputra system and bypasses the eastern foreland basin.

The change from mixed Indus-Yarlung suture zone and Himalayan material to sediments originating only in the Himalaya at ca. 3 Ma can be explained by a southward shift in the foreland basin of the Brahmaputra River because of continuous southward propagation of the Himalayan deformation front. In contrast, the input of suture-zone-derived material between 7 and 3 Ma requires establishment of a drainage connection with the Indus-Yarlung suture zone together with a shift of the Brahmaputra in the foreland basin plain. Several scenarios can be considered, two of which imply changes in the upstream drainage system (Figs. 7A and 7B), one of which implies only local drainage shifts (Fig. 7C), and a final scenario that implies changes in the course of the Brahmaputra River downstream (Fig. 7D).

In the first scenario, the Yarlung and the Brahmaputra Rivers were initially two distinct drainage systems (Brookfield, 1998; Clark et al., 2004; Fig. 7A). The Yarlung River was captured sometime prior to 4 Ma by the steep transverse Brahmaputra-Siang River, as attested by wind gaps and capture points around the Namche Barwa massif (Clark et al., 2004), allowing sediment derived from the Indus-Yarlung suture zone to be deposited between 7 and 3 Ma in the foreland basin. Such a scenario is consistent with our provenance data, but it does not match the record of stable source areas over the past 12 m.y., as inferred from provenance data in the Bengal Fan (Galy et al., 2010). Even if the Yarlung connected to the Irrawaddy River rather than the Red River prior to ca. 7 Ma (cf. Clark et al., 2004), the sediment transported in this system could not have reached the part of the Bengal Fan (Deep Sea Drilling Project [DSDP] site 218) sampled by Galy et al. (2010).

A second scenario was proposed by Cina et al. (2009) and involves a sequence of captures of the Yarlung River that occurred from 7 Ma onward (Fig. 7B), first by the transverse paleo–Subansiri River and later by the Siang-Brahmaputra system. In this scenario, the Yarlung River connected with the Brahmaputra River via a paleo–Subansiri River between ca. 7 Ma and ca. 3 Ma, permitting deposition of sediments derived from the Indus-Yarlung suture zone in the Himalayan foreland basin in what are today the Kameng and Subansiri drainages. Around 3 Ma, the Yarlung River was captured by the Siang-Brahmaputra River, establishing the modern drainage pattern. Such an evolution of the drainage system would require first northwestern headward erosion of the paleo-Subansiri to capture the Yarlung River at 7 Ma, which could be possible if we consider its present-day catchment as the remnant of a larger one. An alternative scenario, in which it was the Kameng River itself that connected to the Yarlung River, appears implausible given the restricted present-day catchment of the Kameng River. Subsequent eastward propagation of deformation and uplift is required to disconnect the upper catchment of the transverse paleo–Subansiri River from the Indus-Yarlung suture zone and allow capture of the Yarlung River by the Siang-Brahmaputra River at ca. 3 Ma. As for the previous scenario implying drainage modification upstream, this scenario is consistent with the local provenance changes in foreland sediments but does not match with the Bengal Fan record, which indicates stable source areas since ca. 12 Ma (Galy et al., 2010). Moreover, there are no geomorphic indications for headward erosion of the Siang River upstream of the Namche Barwa massif (in contrast, the Namche Barwa knickpoint appears to have been fixed for at least the last 1 m.y.; Zeitler et al., 2001; Finnegan et al., 2008; Korup and Montgomery, 2008). Finally, there is no indication for eastward propagation of deformation and uplift in the eastern Himalaya during late Miocene–Pliocene times.

A third scenario implies large-scale stability of the Yarlung-Siang-Brahmaputra drainage system since the late Miocene (Burg et al., 1998; Galy et al., 2010), with local changes only affecting its course in the eastern Himalayan foreland basin after 7 Ma (Fig. 7C). Between 7 and 3 Ma, the Brahmaputra River may have migrated northward, close to the front of the Himalayan belt, as a consequence of surface uplift of the
Shillong Plateau. The timing of surface uplift of the Shillong Plateau is essentially unconstrained but is suggested to follow the onset of exhumation between 8 and 15 Ma (Biswas et al., 2007; Clark and Bilham, 2008). Biswas et al. (2007) suggested northward tilting of the surface of the Shillong Plateau, resulting from faster displacement along the Dauki fault bounding it to the south (Fig. 1) compared to displacement along its northern bounding fault. As a consequence, the depocenter of the foreland basin may have shifted northward, allowing sediments transported by the Brahmaputra River to be deposited in the Kameng area. Our sample locations could have been located near the confluence of a transverse paleo–Kameng River and an E-W–flowing trunk of the paleo–Brahmaputra River. Such a scenario was dismissed by Cina et al. (2009) based on south-directed paleocurrents in the Subansiri area. However, we note that paleocurrent data collected in both the Kameng and Subansiri areas (Fig. 2; Cina et al., 2009) do not provide strong support for any scenario, as the measured paleocurrent directions are highly variable, ranging from N180° to N270° in sedimentary rocks with ages of 12 Ma to ca. 5 Ma. This variability appears consistent with the sedimentological evidence of meandering rivers in the Himalayan foreland basin around that time (Chirouze et al., 2012b). Finally, we note that any measured paleocurrent direction should be corrected for counterclockwise rotation that occurred during thrusting in the Sub-Himalaya in the Kameng area (Chirouze et al., 2012b).

A final scenario, proposed by Uddin and Lundberg (1999), suggests that the Brahmaputra River changed its course during the late Miocene, from east to north of the Shillong Plateau, between 7 and 3 Ma (Fig. 7D). This drainage shift would have resulted from surface uplift of the Shillong Plateau and/or northwestward propagation of the Indo-Burman Ranges. Such an evolution permits the deposition in the contemporaneous Siwalik Group sedimentary rocks and fits with the stable provenance in the distal Bengal Fan sediments (Galy et al., 2010). In contrast, a new chronostratigraphic framework based on biostratigraphy and seismic correlation in the Bengal Basin (Najman et al., 2012) appears to imply that diversion of the paleo–Brahmaputra River to the north of the Shillong Plateau could have taken place as recently as 1 Ma, which is incompatible with our provenance data.

Exhumation of the Eastern Himalaya

The constraints on provenance outlined herein allow us to evaluate the exhumation of various parts of the eastern Himalaya using detrital AFT and ZFT thermochronology applied to the Kameng section sediments. Non-reset AFT ages from the modern Kameng River (KAM 20, KAM 30) and the uppermost part of the stratigraphic section (KAM 8 and KAM 14) provide information on source-area exhumation since ca. 4 Ma. The youngest age population (P1) in these samples has lag times of 1.3–2.9 m.y., indicating relatively rapid exhumation in the range 1.5–2.0 km/m.y. in some parts of the Kameng River source area, whereas the older age component (P2) has lag times >7 m.y., implying that other parts of the catchment were exhumed more slowly, at rates not exceeding 0.6 km/m.y. These results are comparable to those observed in Siwalik Group sections from central and western Nepal, where the youngest AFT age components (P1) have lag times ranging from 0.5 to 4 m.y., and a second age peak (P2) exists with lag times >7 m.y. (van der Beek et al., 2006). Unfortunately, no bedrock AFT ages are currently available in the Kameng River catchment for comparison with detrital AFT ages. Bedrock AFT ages from eastern Bhutan, to the west of the Kameng River catchment, range from ca. 3.5 to >8 Ma (Grujic et al., 2006) and thus appear to record slower exhumation (~0.6–0.9 km/m.y.) than our detrital data.

The detrital ZFT ages of all samples are older than the depositional age and decrease in age up section. They thus record source-area cooling
and are unaffected by burial heating in the basin, consistent with our AFT data, which show incomplete annealing of the deepest buried sedimentary rocks sampled for this study. Based on the $\varepsilon_{Nd}$ provenance information discussed previously, the lag times of the youngest (P1) detrital zircon age population of sedimentary rocks deposited between 13 and 8 Ma and from $<3$ Ma to the present can be used to estimate exhumation rates for the eastern Himalaya. The P1 lag times are on average $\approx 4$ m.y., implying exhumation rates on the order of 1.8 km/m.y. for the most rapidly exhuming source areas (Fig. 8). Between 7 and 3 Ma, sediments were probably deposited by the Yarlung-Brahmaputra River and should thus include zircons derived from the Namche Barwa massif in the eastern syntaxis. During this time interval, the weighted-mean lag time of the youngest (P1) age population is a bit shorter (3 m.y. instead of 4 m.y.). Nonetheless, all ZFT age peaks in the Kameng section exhibit overall constant trends through time, and are comparable to data from Nepal (Fig. 9; Bernet et al., 2006; Chirouze et al., 2012a). As in the central Himalaya, the zircons generally show three age peaks: two static peaks (i.e., displaying constant peak ages through time; see Garver et al., 1999; Bernet et al., 2006), and one moving peak with a constant lag time of $\approx 4$ m.y. The average proportion of zircons belonging to each of these age populations is fairly similar in the Kameng section (P1, P2, and P3 age components are 44%, 42%, and 15%, respectively) and in central Nepal (50%, 36%, and 21%, respectively; Bernet et al., 2006).

Therefore, our ZFT and unreset AFT results suggest that the exhumation dynamics in the eastern Himalaya were similar to those of the central Himalaya (Bernet et al., 2006; van der Beek et al., 2006), at least for the sediments deposited between 13 and 7 Ma and since 3 Ma. Therefore, these results do not support the hypothesis of a deceleration in thrusting and exhumation rates in the eastern Himalaya since the mid-Miocene, linked to potential transfer of shortening to the Shillong Plateau (Clark and Bilham, 2008). Surface uplift of the Shillong Plateau does not appear to strongly affect long-term exhumation rates in the eastern Himalaya, and, therefore, the proportion of tectonic shortening accommodated by this structure may be limited, as previously suggested by Biswas et al. (2007) and observed in GPS studies (Mukul et al., 2010).

A reduction of exhumation rates at ca. 6 Ma has been suggested for the Bhutan Himalaya, inferred from in situ AFT data and the preservation of elevated paleosurfaces (Grujic et al., 2006). Slower exhumation rates compared to the central Himalaya were attributed to the decrease
of monsoon intensity caused by surface uplift of the Shillong Plateau (Grujic et al., 2006; Biswas et al., 2007). Our data, collected ~130 km east of Bhutan, do not support such an overall decrease in exhumation rates, despite similar precipitation intensities and patterns in Arunachal Pradesh and eastern Bhutan (Bookhagen and Burbank, 2006). Thus, it seems that the variation of exhumation rates between Bhutan and Arunachal Pradesh is controlled by tectonic rather than climatic variations. The geometry of the crustal detachment underlying the belt (Main Himalayan Thrust) and especially the presence or absence of a crustal ramp could control spatial variations in exhumation patterns along the Himalaya (Berger et al., 2004; Robert et al., 2011). The pattern of exhumation in Bhutan is consistent with the absence of a major ramp (e.g., McQuarrie et al., 2008; Long et al., 2011), whereas our data from Arunachal Pradesh would suggest that such a ramp reappears further east, consistent with the structural cross sections recently compiled by Yin et al. (2010).

**Exhumation of the Namche Barwa Massif**

The detrital isotopic signature described here, together with zircon U-Pb ages (Cina et al., 2009), suggests that Siwalik Group sediments in the Kameng section were deposited by a paleo-Brahmaputra River between ca. 7 Ma and 3 Ma. The $e_{U}/e_{H}$ values of these sediments are very similar to those of the present-day Brahmaputra River sediments, and Singh and France-Lanord (2002) have shown that this signal can be explained by a mixture of sediment derived from Indus-Yarlung suture zone rocks and Himalayan rocks from the Namche Barwa massif, with very little dilution by tributaries draining the eastern Himalaya. Cina et al. (2009) showed that in their sample containing zircons from the Gangdese Batholith, the Himalayan contribution is ~70%, consistent with estimates of the present-day contribution of Namche Barwa–derived sediments in the Brahmaputra bed load (Singh and France-Lanord, 2002; Enkelmann et al., 2011).

Therefore, the majority of zircons in the ca. 7 Ma to 3 Ma sediments should be derived from the Namche Barwa syntaxis, and the young detrital ZFT age peak should record cooling of the eastern syntaxis during that time. Exhumation rates calculated for the youngest (P1) ZFT age population for this period are, however, similar to those above and below this part of the section (1.5–2.0 km/m.y.; Fig. 7). Keeping in mind the loss of resolution when estimating very rapid exhumation rates from lag times (e.g., Garver et al., 1999; Rahl et al., 2007), the recorded late Miocene exhumation rates appear to be significantly slower than the Quaternary rate of up to 10 km/m.y. inferred from in situ thermochronology in the Namche Barwa massif by Burg et al. (1998) and detrital ZFT data of Stewart et al. (2008). Such extreme present-day exhumation rates are also required by the detrital ZFT age patterns of the modern Siang River sediment load downstream of the Yalung gorge, where 60%–70% of the detrital zircons belong to a ZFT age population averaging only 0.6 Ma, suggesting source-area exhumation rates of 7–9 km/m.y. (Enkelmann et al., 2011).

This contrast suggests that rapid exhumation in the Namche Barwa massif did not begin before 4 Ma. This result is consistent with estimates of the onset of exhumation inferred from in-situ analyses, which indicate that the Namche Barwa massif has been exhumed extremely rapidly (up to 10 km/m.y.) over the past 4 m.y. (Burg et al., 1998), although arguments for an earlier (ca. 6–11 Ma) onset of exhumation have also been made (Ding et al., 2001; Booth et al., 2009). Because the Yarlung-Brahmaputra River has been flowing across the eastern syntaxis since at least 7 Ma, a minimum 3 m.y. time lag appears to separate capture of the Yarlung River by the Siang-Brahmaputra and the onset of the currently observed very rapid exhumation. This time lag may correspond to a response time required for initiation of strong feedbacks between tectonics and Siang River incision (Zeitler et al., 2001; Finnegan et al., 2008) or, alternatively, may point to an additional (climatic?) trigger required to initiate very rapid exhumation.

**Deformation and Exhumation of the Siwaliks in the Eastern Himalaya**

Samples from below ~2000 m stratigraphic depth in the section (except sample KAM 5) contain apatite with partially reset cooling ages (Fig. 5; Table 2), as they show central and/or minimum (P1) AFT ages younger than or equal to their depositional age, within error. The central age evolution with depth does not show a clearly defined AFT partial annealing zone (Fig. 5). Sample KAM 5 escaped partial annealing, while samples stratigraphically above and below this sample were partially annealed. The pattern of partial resetting in the section is complicated by activity of the Tipi thrust, which led to additional tectonic burial of part of the footwall, and is thus not simply controlled by burial heating during sediment deposition (Fig. 5). Despite these structural complications, the youngest (P1) population of the stratigraphically lowest and most strongly annealed samples, KAM 11, KAM 12, and KAM 16, can be used to provide a maximum age for the onset of exhumation of the hanging wall of the Tipi thrust (Fig. 5). KAM 12 and KAM 11 present P1 ages of ca. 0.7 Ma, whereas KAM 16 presents a P1 age of ca. 2 Ma. The youngest age peak could not be detected in sample KAM 16, even though this is the stratigraphically lowest sample collected; the young age peak could be mixed with an older population. We thus interpret these data to suggest onset of activity of the Tipi thrust close to 1 Ma. If we assume southward propagation of thrust activity as in Nepal (e.g., Mugnier et al., 2004), then initiation of the Main Frontal thrust must significantly postdate 1 Ma in the area (Fig. 5).

The initiation age of the Main Frontal thrust can be estimated independently using the sedimentary record. Since no piggyback basins have developed along the Kameng section (Yin et al., 2010), no sedimentation occurred within the Sub-Himalaya during the activity of this thrust. The depositional age of the youngest outcrop of the Kimin Formation (upper Siwalik Group) along the section can be estimated using the sedimentation rate calculated in the top part of the section. With this hypothesis, the youngest upper Siwalik sediments would have been deposited after 1 Ma, and thus the onset of motion on the Main Frontal thrust should have occurred after this time, consistent with our AFT data.

In western Nepal, AFT results and field observations indicate that the Main Frontal thrust initiated around 2 Ma, although rates of thrusting may have increased significantly after ca. 0.3 Ma (Mugnier et al., 2004; van der Beek et al., 2006). Our results thus suggest that Main Frontal thrust activity initiated some 1 m.y. later in the eastern Himalaya.

**CONCLUSIONS**

Our geochemical and thermochronological analyses of foreland basin sedimentary rocks allow us to reconstruct the unroofing history and the evolution of the main drainage system in the eastern Himalaya. These data lead us to the following conclusions:

1. The evolution of the sedimentary provenance along the Kameng section, from one dominated by Himalayan tributaries to one dominated by the Yarlung-Brahmaputra, indicates that a major reorganization of the Yarlung-Siang-Brahmaputra drainage system occurred in the foreland at ca. 7 Ma. The contemporaneous activity of the Indo-Burman Ranges and surface uplift of the Shillong Plateau could have diverted the paleo-Brahmaputra River to the north and forced it to flow along the foothills of the Himalayan Range. Southward propagation of thrusting in the Himalayan foreland after 3 Ma subsequently pushed the river south to its present course.

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2. Fission-track ages from sediments deposited between 13 and 7 Ma and between ca. 3 Ma and 0 Ma record exhumation of the eastern Himalaya. Both zircon and apatite present similar lag-time trends to those in Nepal. The evolution of exhumation rates inferred from our thermochronologic results is not consistent with a postulated decrease in exhumation rates caused by either reduced shortening rates or reduced precipitation in response to surface uplift of the Shillong Plateau.

3. Zircon fission-track analysis of sediments deposited between 7 and 3 Ma, derived from the suture zone and the eastern syntaxis, do not present young ZFT age peaks with very short lag times, as is observed today for the very rapidly exhuming Namche Barwa massif. Therefore, exhumation in the eastern syntaxis was ~5 times slower at that time than it is today. This result suggests a lag time of at least 3 m.y. from the installation of a transverse river in the eastern syntaxis to the onset of very rapid exhumation in the Namche Barwa massif.

4. Forward propagation of deformation in the Sub-Himalaya in Arunachal Pradesh led to activation of the Tipi thrust by ca. 1 Ma. The onset of activity on the Main Frontal thrust is therefore locally younger than 1 Ma.

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