

1 **The Brahmaputra tale of tectonics and erosion: Early Miocene**
2 **river capture in the Eastern Himalaya**

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14

15 **ABSTRACT**

16 The Himalayan orogen provides a type example on which a number of models of the causes and
17 consequences of crustal deformation are based and it has been suggested that it is the site of a variety
18 of feedbacks between tectonics and erosion. Within the broader orogen, fluvial drainages partly reflect
19 surface uplift, different climatic zones and a response to crustal deformation. In the eastern Himalaya,
20 the unusual drainage configuration of the Yarlung Tsangpo–Brahmaputra River has been interpreted
21 either as antecedent drainage distorted by the India-Asia collision (and as such applied as a passive
22 strain marker of lateral extrusion), latest Neogene tectonically-induced river capture, or glacial
23 damming-induced river diversion events.

24 Here we apply a multi-technique approach to the Neogene paleo-Brahmaputra deposits of the Surma
25 Basin (Bengal Basin, Bangladesh) to test the long-debated occurrence and timing of river capture of
26 the Yarlung Tsangpo by the Brahmaputra River. We provide U-Pb detrital zircon and rutile, isotopic
27 (Sr-Nd and Hf) and petrographic evidence consistent with river capture of the Yarlung Tsangpo by the
28 Brahmaputra River in the Early Miocene. We document influx of Cretaceous-Paleogene zircons in
29 Early Miocene sediments of the paleo-Brahmaputra River that we interpret as first influx of material
30 from the Asian plate (Transhimalayan arc) indicative of Yarlung Tsangpo contribution. Prior to
31 capture, the predominantly Precambrian-Paleozoic zircons indicate that only the Indian plate was
32 drained. Contemporaneous with Transhimalayan influx reflecting the river capture, we record arrival
33 of detrital material affected by Cenozoic metamorphism, as indicated by rutiles and zircons with
34 Cenozoic U-Pb ages and an increase in metamorphic grade of detritus as recorded by petrography. We
35 interpret this as due to a progressively increasing contribution from the erosion of the metamorphosed
36 core of the orogen. Whole rock Sr-Nd isotopic data from the same samples provide further support to
37 this interpretation. River capture may have been caused by a change in relative base level due to uplift
38 of the Tibetan plateau. Assuming such river capture occurred via the Siang River in the Early
39 Miocene, we refute the “tectonic aneurysm” model of tectonic-erosion coupling between river capture
40 and rapid exhumation of the eastern syntaxis, since a time interval of at least 10 Ma between these two
41 events is now demonstrated. This work is also the first to highlight U-Pb dating on detrital rutile as a

42 powerful approach in provenance studies in the Himalaya in combination with zircon U-Pb
43 chronology.

44 Keywords: Brahmaputra; Yarlung Tsangpo; Eastern Himalaya; river capture; U-Pb chronology; rutile.

45 **1. Introduction**

46 Studies of crustal-scale orogenic systems provide important insights into processes of intra-
47 continental deformation and the dynamic links between continental tectonics, surface processes,
48 climate feedbacks and the biosphere on a global scale. The extent, rate and timing of erosion influence
49 the metamorphic and structural evolution of mountain belts (England and Richardson, 1977;
50 Beaumont et al., 1992; Willett et al., 1993) as well as influencing their exhumation pattern and rate
51 (e.g. Beaumont et al 2001; Zeitler et al., 2001a; Robl et al., 2008). In this context, the investigation of
52 fluvial drainage evolution provides a key to understanding tectonic-erosion interactions. Importantly,
53 the reorganization of drainage systems can also heavily affect the nature, magnitude and spatial
54 distribution of sediment supply to sedimentary basins by significantly changing the size of the
55 hinterland catchment area.

56 In the eastern Himalaya, assessment of paleodrainage networks has been used to document
57 crustal strain (Hallet and Molnar, 2001) and surface uplift (Clark et al., 2004; Stüwe et al., 2008). In
58 this region the modern Yarlung Tsangpo River, one of the main rivers of Asia, flows east along the
59 suture zone which separates the Indian plate in the south from the Asian plate to the north, then
60 crosses the Namche Barwa massif of the eastern Himalayan syntaxis where it bends sharply south,
61 traverse to the Himalaya as the Siang River and finally flows to the Bengal plains as the Brahmaputra
62 River (Fig. 1).

63 Considerable debate has existed as to whether the Yarlung Tsangpo–Brahmaputra
64 paleodrainage: i) having maintained its current routing without river capture was antecedent to
65 Himalayan orogenesis (Harrison et al., 1992 and references therein); ii) was antecedent to the
66 development of the Namche Barwa syntaxis (that occurred < 4 Ma according to Seward and Burg,
67 2008; see also Lang and Huntington, 2014); or iii) whether the Yarlung Tsangpo originally flowed

68 southeast and eventually connected to the Brahmaputra via one or more capture events (e.g. Seeber
69 and Gornitz, 1983; Brookfield, 1998; Clark et al., 2004; Cina et al., 2009; Chirouze et al., 2012a).
70 Some authors have even suggested that the Yarlung Tsangpo may have reversed its flow (Burrard and
71 Hayden, 1907; Cina et al., 2009).

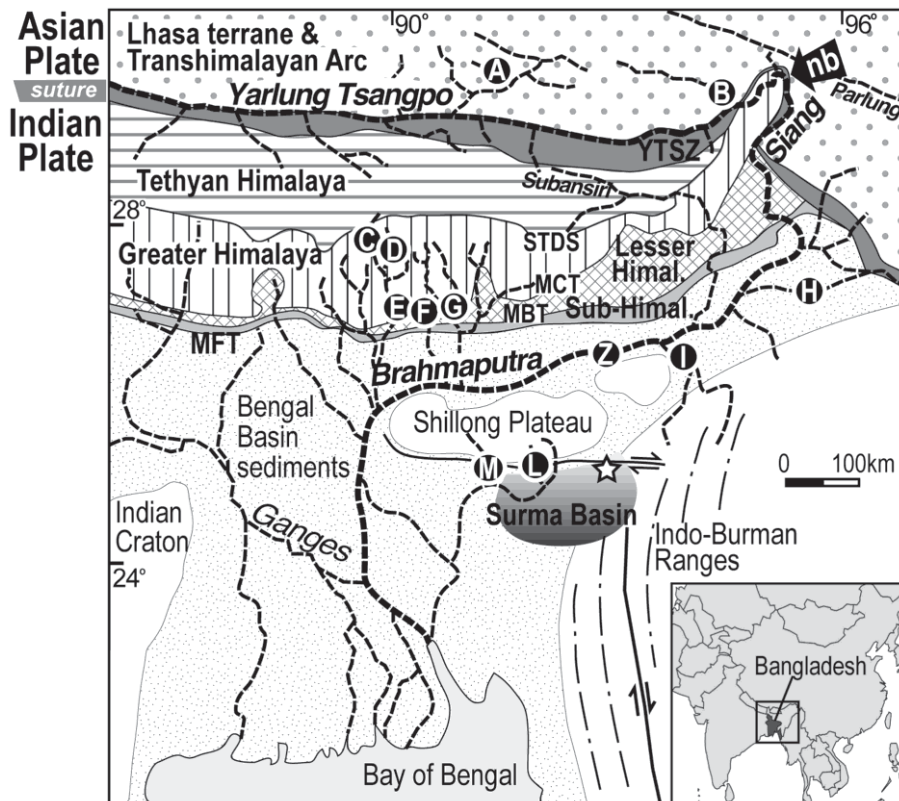
72 In this paper we use the term *river capture* (also known as *river piracy*) to indicate the type of
73 drainage rearrangement (i.e. transfer of a river's flow to another river) that occurs with the
74 interception of a river by an adjacent river which is experiencing aggressive headward erosion
75 (Bishop, 1995). The point at which river capture is considered to have occurred is taken to be
76 indicated by a sharp change in channel direction, known as the elbow of capture, and implies capture
77 of both the catchment area and the drainage lines (the drainage network) above the elbow.
78 Considerably lower elevation of the capturing stream is essential to provide the steep headwater
79 gradients necessary for stream piracy. The other two types of drainage reorganisation (Bishop, 1995)
80 are *river diversion* (redirection of drainage into an adjacent catchment by a range of mechanisms of
81 divide breaching, including channel migration, tectonic processes such as tilting or doming, or
82 catastrophic avulsion by high magnitude water flows) and *river beheading* (the appropriation of a
83 river's catchment area to an adjacent river without preservation of the appropriated catchment's area
84 drainage lines that results, for example, in truncated valleys hanging in the escarpment as a result of
85 escarpment retreat).

86 The river capture of the Yarlung Tsangpo by the Brahmaputra has been cited as the cause of
87 the recent rapid exhumation and young metamorphism of the Namche Barwa syntaxis (the proposed
88 site of capture, Fig. 1), and is thought to be an example of tectonic-erosion coupling (Zeitler et al.,
89 2001b). However, independent tests of the occurrence and timing of river capture are sparse and a
90 general consensus has not been reached. Seeber and Gornitz (1983), although arguing for a general
91 antecedence of the Himalayan rivers with respect to the Himalayan topography, did not rule out a
92 possible capture of an ancestral Yarlung Tsangpo–Lohit River by the Brahmaputra. Brookfield (1998)
93 suggested that an ancestral Tsangpo-Irrawaddy was truncated by headward erosion from the
94 Brahmaputra not earlier than the Late Miocene. According to Zeitler et al. (2001b) the rapid fluvial
95 incision likely following capture of the Yarlung Tsangpo by the Brahmaputra caused the very rapid

96 recent exhumation of the Indian plate metamorphic rocks of the Namche Barwa syntaxis during the
97 Plio-Pleistocene. Clark et al. (2004) suggested that the Yarlung Tsangpo was sequentially captured by
98 the paleo-Red, Irrawaddy and Lohit Rivers, before its final capture by the Brahmaputra occurred prior
99 to 4 Ma, based on the proposed age of the localised uplift of the Namche Barwa syntaxis, whilst
100 Seward and Burg (2008) argued for the existence of an antecedent Yarlung Tsangpo–Brahmaputra
101 drainage probably since ~20 Ma.

102 Cina et al. (2009) and Chirouze et al. (2012a) observe Transhimalayan arc provenance in the
103 Siwalik foreland basin south-west of the syntaxis by 7 Ma while Lang and Huntington (2014) possibly
104 by 13 Ma (based on the correlation to the dated Siwaliks section of Chirouze et al., 2012b). Each of
105 the three studies speculates on alternative scenarios for the evolution of the Yarlung Tsangpo,
106 requiring either a transverse river (such as the Kameng or Subansiri) or a paleo-Yarlung Tsangpo–
107 Brahmaputra (antecedent according to Lang and Huntington, 2014 or not antecedent according to Cina
108 et al., 2009 to the growth of the Namche Barwa syntaxis) to deliver Transhimalayan Arc-derived
109 detritus to the Siwalik foreland basin. These models are further discussed at the end of section 5.

110 We have applied a multi-disciplinary approach (including whole rock petrographic and
111 isotopic data and detrital single grain U-Pb dating) to the paleo-Brahmaputra sedimentary record
112 preserved in the northern Bengal Basin (Surma Basin, Fig.1) in order to constrain the paleodrainage
113 evolution of the Brahmaputra. In particular we address whether capture of the Yarlung Tsangpo
114 occurred and if so when this happened. Finally, we interpret our results in the wider context of
115 regional Himalayan tectonic events.



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128 2. Geology of the modern-day Yarlung Tsangpo–Brahmaputra catchment

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The Ganges and Yarlung Tsangpo–Brahmaputra rivers drain the Himalaya and converge in Bangladesh to form one of the world’s largest sub-aerial fluvio-deltaic systems (the present-day

131 Bengal Basin, Fig. 1) and the world's largest submarine fan system (the Bengal Fan). The Yarlung
132 Tsangpo originates in Tibet and flows eastwards along the Indus-Tsangpo Suture Zone that separates
133 the Indian plate from the Asian Plate (Fig. 1; see Hodges, 2000; Yin, 2006 and Yin et al., 2010a, for a
134 review of Himalayan geology). North of the suture lies the Lhasa terrane, the southernmost of the four
135 continental blocks comprising the Tibetan Plateau, and the Jurassic–Paleogene Transhimalayan Arc
136 resulting from the northward subduction of the Neo-Tethys slab along the southern margin of Asia
137 (Harris et al., 1990; Copeland et al., 1995). The basement of the Lhasa terrane is comprised of
138 Precambrian gneisses and Paleozoic to Mesozoic sedimentary covers (Zhu et al., 2011).

139 South of the suture, the South Tibetan Detachment System separates the Tethyan Himalaya
140 (TH, mainly a Paleozoic–Eocene sedimentary succession which was deposited on the northern passive
141 margin of India) from the Indian plate rocks of the Greater Himalaya (GH), metamorphosed across
142 amphibolite to lower granulite-facies conditions during the Cenozoic orogeny (Kohn, 2014). Burial
143 and heating of GH culminated in crustal melting and emplacement of Neogene leucogranites (Guo and
144 Wilson, 2012). The Main Central Thrust separates GH from the Lesser Himalaya (LH, mainly
145 Proterozoic metasedimentary sequence, typically greenschist facies or unmetamorphosed sedimentary
146 cover deposited on Indian crust). The Sub-Himalaya consists of Cenozoic foreland basin sediments
147 lying between LH and the active thrust front of the orogen (Hodges, 2000).

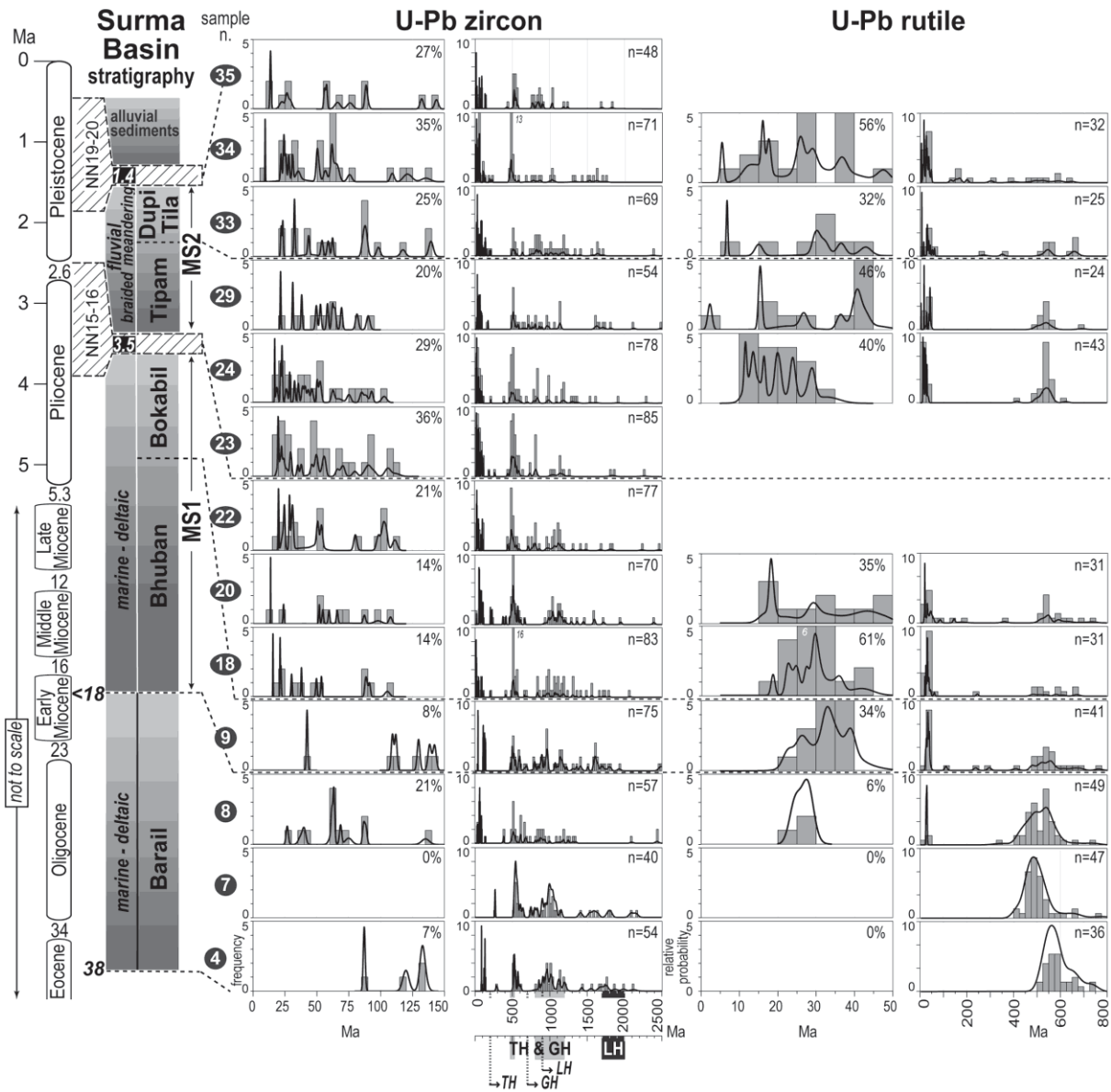
148 **3. The paleo-Brahmaputra sedimentary record (Surma Basin)**

149 Most of the Bengal Basin fill consists of sediments fluvially transported by the Ganges and
150 Brahmaputra and their ancestral river systems (e.g. the “proto-Ganges Brahmaputra river systems” of
151 Roybarman, 1983; Johnson and Nur Alam, 1991; Reimann, 1993; Uddin and Lundberg, 1998; 1999;
152 Najman et al., 2008; Najman et al., 2012). The Surma Basin (Fig. 1), a sub-basin of the Bengal Basin
153 in north-eastern Bangladesh, is bordered to the north by the Shillong Plateau, the only raised
154 topography in the foreland of the Himalaya, that consists of Indian plate Precambrian basement
155 partially overlain by Cenozoic sediments (Yin et al., 2010b). To the east the Surma Basin is bordered
156 by the Cenozoic Indo-Burman Ranges fold and thrust belt which is propagating west and is

157 responsible for the north-south trending folding in the Bengal Basin. To the west, the adjacent
158 highland is the Precambrian Indian plate, and to the south the region drains to the Bay of Bengal.

159 The 16 km-thick succession of Eocene-Pleistocene limestone and clastic rocks preserved in
160 the Bengal Basin was deposited on the Indian continental margin that includes the Surma Basin (Fig.
161 1). Above the Eocene Sylhet Formation limestone and Kopili Formation black shale, the Oligocene-
162 Early Miocene deltaic sandstone of the Barail Formation record the first major clastic influx from the
163 Himalaya (Najman et al., 2008). Above the Barail Formation (Fig. 2) lies the Neogene Surma Group
164 (Bhuban and Bokabil Formations) and the Tipam and Dupi Tila Formations which show facies
165 evolution from deltaic to fluvial environments (Johnson and Nur Alam, 1991; Fig. 2). Earlier dating of
166 the Bengal Basin Formations by lithostratigraphic correlation with rocks far to the north in Assam
167 (Evans, 1932) proved problematic within a deltaic system with high rates of subsidence and rapid
168 facies changes. The samples from this study (Supplemental Table S1) were checked for occurrence of
169 foraminifera, but proved to be either barren or containing sporadic reworked or badly preserved long-
170 ranging benthic species. In order to overcome the limitations of the lithostratigraphic approach, we
171 adopt the seismo-stratigraphic correlation approach of Najman et al. (2012). According to this
172 approach, the Neogene succession has been divided into seismically distinct, unconformity-bounded
173 and regionally correlatable Megasequences (MS in Fig. 2). MS1 is equivalent to the Bhuban and
174 Bokabil Formations, MS2 to the Tipam and Dupi Tila Formations and MS3 is not represented in the
175 Surma Basin. In this basin the boundary between the marine-deltaic seismic megasequence MS1 and
176 the fluvial MS2 lies within nannoplankton zones NN15-NN16, in agreement with a
177 magnetostratigraphic date of 3.5 Ma (Worm et al., 1998). The top of MS2 lies within zones NN19-
178 NN20 and is constrained at 1.4 Ma in the study area by magnetostratigraphy (Worm et al., 1998). The
179 Early Pliocene age for the upper Bhuban Formation is indicated by stratigraphic (Lietz and Kabir,
180 1982) and magnetostratigraphic data (Worm et al., 1998). The lower boundary of MS1 is constrained
181 at <18 Ma by the occurrence of detrital white mica in uppermost Barail and lowermost Bhuban
182 samples dated by Ar-Ar at 21 ± 3 (Najman et al., 2008) and 14 ± 4 Ma (Bracciali, unpublished data),
183 respectively. This is in agreement with prominent modes of Ar-Ar white mica dates of 16–18 Ma in
184 Bhuban samples from well penetrations (Uddin et al., 2010), in which the youngest mica grains in

185 three Bhuban samples of increasing stratigraphic depth are dated at 12.3 ± 0.6 Ma (upper Bhuban,
186 well Beani-Bazar-1X; cf. well stratigraphy in Reimann, 1993), 16.8 ± 0.6 Ma and 19.3 ± 0.8 (lower
187 Bhuban, well Fenchuganj-2; cf. well stratigraphy in Deb et al., 2014). The base of the Barail
188 Formation is constrained at 38 Ma by biostratigraphy (Najman et al., 2008).



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Fig. 2. Surma Basin schematic stratigraphy and detrital U-Pb data from this study. The stratigraphic boundaries are constrained with variable degree of confidence as detailed in main text by biostratigraphy (Lietz and Kabir, 1982; Najman et al., 2012; NN: nannoplankton zones), magnetostratigraphy (Worm et al., 1998) and detrital mineral dates (Najman et al., 2008; Uddin et al., 2010). MS: Megasequence. See Supplementary Material for sample description and U-Pb data. Relative probability plots and frequency diagrams of zircon and rutile single grain U-Pb data are plotted in the range 0–150 and 0–50 Ma, respectively, and in the 0–2.5 and 0–0.8 Ga range. Percentages: number of grains younger than 150 and 50 Ma as compared to n, the total number of individual ablations after rejection of discordant zircon

199 datapoints (Supplemental Table S2) and common Pb correction of discordant rutile datapoints
200 (as described in Bracciali et al., 2013; Supplemental Table S4). Concordia diagrams are in
201 Supplemental Fig. S4. Light and dark grey bands represent the main age peaks of detrital
202 zircons in TH, GH, and LH based on literature data; dashed vertical lines indicate the
203 youngest populations generally found in the same formations in the eastern Himalaya (see text
204 for references and cf. Fig. 3).

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206 Whilst most workers are in agreement that the majority of the Neogene sediment in the
207 Bengal Basin is Himalayan-derived (e.g. Johnson and Nur Alam, 1991; Uddin and Lundberg, 1998;
208 Uddin et al., 2010), there is considerable debate as to the degree of input from the Indo-Burman
209 Ranges and Shillong Plateau, the timing of river capture when material from north of the suture zone
210 first entered the basin, and the time when the Brahmaputra diverted west of the Shillong Plateau
211 (Johnson and Nur Alam, 1991; Brookfield, 1998; Zeitler et al., 2001a; Clark et al., 2004; Cina et al.,
212 2009; Uddin et al., 2010; Chirouze et al., 2012a).

213 **4. Methods**

214 **4.1 Laser Ablation U-Pb dating of zircon and rutile**

215 Laser ablation (LA) U-Pb data were collected at the NERC Isotope Geosciences Laboratory
216 (NIGL) using either a 193 nm or a 213 nm wavelength laser ablation system coupled to a Nu Plasma
217 HR multiple-collector inductively coupled plasma mass spectrometer (MC-ICP-MS). The mass
218 spectrometer used has a specially designed collector block to allow simultaneous detection of all
219 masses in the range 202–207, 235 and 238. Methods followed those described in Thomas et al. (2010).
220 Instrument parameters used during analysis are detailed in Supplemental Table S5. Analysis was
221 performed using the Time Resolved Analysis (TRA) mode of the Nu Plasma software with signals
222 integrated excluding the first 3–5 s of data and the data normalised and uncertainty propagated offline
223 using an in-house Excel spreadsheet. After an initial 30 s instrument baseline measurement and 30 s
224 gas blank, individual analysis ablation times were 40 s for a run of 10–15 ablations. The simultaneous
225 measurement of the ^{202}Hg signal allows correction for the isobaric interference of ^{204}Hg on ^{204}Pb

226 during the ablation. A desolvating nebuliser (DSN-100, Nu Instruments) was used to simultaneously
227 aspirate a solution containing Tl (with isotopes 203 and 205) and ^{235}U in order to correct for mass
228 spectrometer-related mass bias (Pb/Pb ratios using $^{205}\text{Tl}/^{203}\text{Tl}$, Pb/U ratios using $^{205}\text{Tl}/^{235}\text{U}$) at the time
229 of analysis. Elemental fractionation from other sources (laser- and plasma-induced) was corrected by
230 comparison of laser ablation data for a primary reference material to ID-TIMS data.

231 Uncertainties for the $^{207}\text{Pb}/^{206}\text{Pb}$ ratios were propagated using quadratic addition to combine
232 the measurement uncertainty with a reproducibility component modelled to reflect increasing
233 uncertainty with decreasing signal size. A minimum uncertainty of 0.5% (2σ) was assigned to the
234 $^{207}\text{Pb}/^{206}\text{Pb}$ ratio by default for ablations with high ^{207}Pb ion beams, to reflect the confidence in the
235 ability of the multi-ion counting (MIC) set-up to accurately reproduce any one value. $^{206}\text{Pb}/^{238}\text{U}$
236 uncertainties were propagated in a similar way utilising the measurement uncertainty and the
237 reproducibility of the ablation reference material used.

238 During each analytical session both zircon and rutile reference materials were measured
239 between each group of unknowns to determine the degree of elemental fractionation, to monitor the
240 effect of matrix on the degree of elemental fractionation, and to assess instrumental accuracy
241 (Supplemental Tables S2, S4 and S5).

242 Cathodoluminescence images of all zircons were acquired prior to LA work and both cores
243 and rims were analysed. Where thin rims $< 10\text{--}5\ \mu\text{m}$ were identified on CL images, the grain was
244 removed from mount and the outer surface ablated. Discordant zircon datapoints (Supplemental
245 Figures S3 and S4 and Tables S2 and S4) were not included in the probability plots of Figures 2 and 3.
246 Discordant rutile datapoints were common Pb corrected as described in Bracciali et al. (2013). When
247 two zircon or rutile dates from the same grain overlapped within uncertainty, only the one determined
248 with the lower uncertainty was included in the final probability plot.

249 **4.2 Zircon Hf isotope analysis**

250 Isotope analyses were carried out at NIGL using a Thermo Scientific Neptune Plus MC-ICP-
251 MS coupled to a New Wave Research UP193FX Excimer laser ablation system and low-volume
252 ablation cell. Helium was used as the carrier gas through the ablation cell with Ar make-up gas being

253 connected via a T-piece and sourced from a Cetac Aridus II desolvating nebulizer. After initial set-up
254 and tuning a 2% HNO₃ solution was aspirated during the ablation analyses. Lutetium (¹⁷⁵Lu),
255 Ytterbium (¹⁷²Yb, ¹⁷³Yb), and Hafnium (¹⁷⁶Hf, ¹⁷⁸Hf, ¹⁷⁹Hf and ¹⁸⁰Hf) isotopes were measured
256 simultaneously during static 30 s ablation analyses (50 μm; fluence = 8–10 J/cm²).

257 Hf reference solution JMC475 was analyzed during the analytical session and sample
258 ¹⁷⁶Hf/¹⁷⁷Hf ratios are reported relative to a value of 0.282160 for this standard (Supplemental Table
259 S3). Correction for ¹⁷⁶Yb on the ¹⁷⁶Hf peak was made using reverse-mass-bias correction of the
260 ¹⁷⁶Yb/¹⁷³Yb ratio empirically derived using Hf mass bias corrected Yb-doped JMC475 solutions. ¹⁷⁶Lu
261 interference on the ¹⁷⁶Hf peak was corrected by using the measured ¹⁷⁵Lu and assuming ¹⁷⁶Lu/¹⁷⁵Lu =
262 0.02653. Two zircon reference materials (91500 and Mud Tank) were analysed throughout the
263 analytical session. 16 analyses of Mud Tank gave a mean ¹⁷⁶Hf/¹⁷⁷Hf value of 0.282515 ± 0.000013
264 (1σ). 48 analyses of the 91500 reference material showed considerably more scatter, with a mean
265 value of 0.282309 ± 0.000021 (1σ). 91500 zircon reference material was used to normalise the
266 ¹⁷⁶Lu/¹⁷⁷Hf ratio assuming a value of 0.000311.

267 Analytical uncertainties for unknowns were propagated by quadratic addition to include the
268 standard error of the mean of the analysis and the reproducibility of the Mud Tank reference material.

269 **4.3 Modal analysis of sandstones**

270 In each arenite sample 400 points were counted at the British Geological Survey,
271 Nottingham, by the Gazzi-Dickinson method (Ingersoll et al., 1984) to minimise the dependence of
272 arenite composition on grain size. Calculated grain parameters are presented in Supplemental Table
273 S6. Metamorphic lithic grains were classified according to protolith composition and metamorphic
274 rank (Garzanti and Vezzoli, 2003). Average rank for each sample was expressed by the “Metamorphic
275 Index” MI, which varies from 0 in detritus from sedimentary and volcanic cover rocks to 500 in
276 detritus from high-grade basement rocks (Garzanti and Vezzoli, 2003). Very low to low-rank
277 metamorphic lithics, for which protolith can still be inferred, were subdivided into metasedimentary
278 (Lms) and metavolcanic (Lmv) categories. Medium to high-rank metamorphic lithics were subdivided
279 into felsic (metapelite, metapsammite, metafelsite; Lmf) and mafic (metabasite; Lmb) categories.

280 **4.4 Whole rock Sr and Nd isotope analysis**

281 For Sr and Nd analysis, powders obtained from samples were leached at NIGL in 10% acetic
282 acid in order to remove carbonate. Subsequently, the samples were spiked with ^{84}Sr and ^{150}Nd isotope
283 tracers and dissolved using HF and HNO_3 . After an initial separation using Dowex AG50X8 cation
284 exchange resin, Sr was separated using EICHRON Sr-Spec resin, and Nd was separated using LN-
285 Spec resin. Sr was loaded on single Rhenium filaments using a TaO activator and analysed in
286 multidynamic mode on a Thermo Triton mass spectrometer. Nine analyses of SRM987 gave a mean
287 $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.710250 ± 0.000006 (1σ). Nd was loaded on rhenium double filaments and
288 analysed in multidynamic mode on a Thermo Triton mass spectrometer. Five analyses of the La Jolla
289 standard gave a mean $^{143}\text{Nd}/^{144}\text{Nd}$ value of 0.511847 ± 0.000007 (1σ).

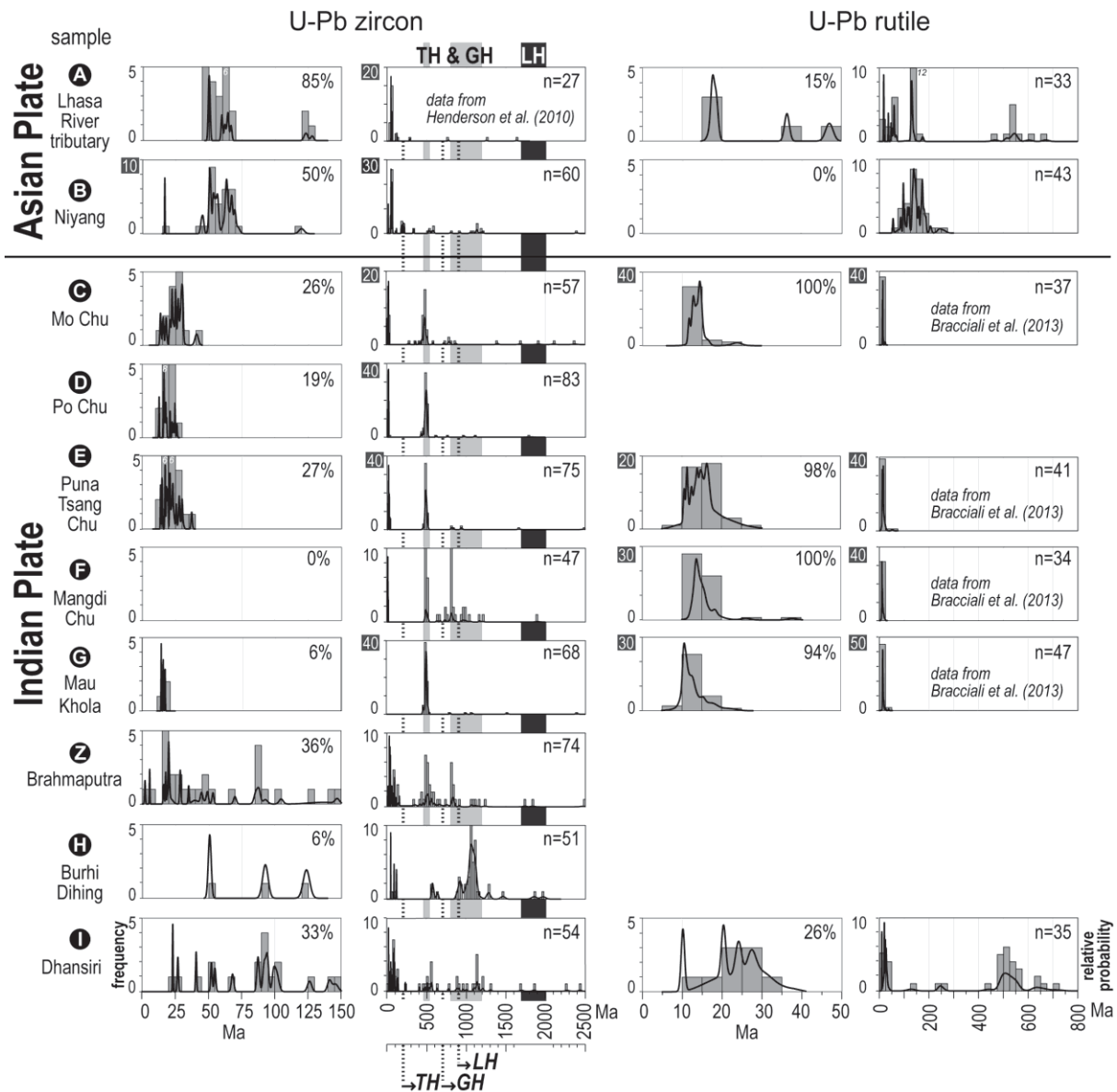
290 **5. Early Miocene river capture of the Yarlung Tsangpo by the Brahmaputra River**

291 As detailed in section 2, the Asian plate, along which the Yarlung Tsangpo flows, contains a
292 very different geology to the Indian plate, which would have been the predominant contributing
293 source region of the paleo-Brahmaputra prior to the river capture of the Yarlung Tsangpo. Distinctive
294 of the southern margin of the Asian plate are the pre-collisional Jurassic-Paleogene subduction-related
295 granitoids of the Transhimalayan batholiths intruding the Lhasa Terrane (see review in Zhu et al.,
296 2011). The Linzizong volcanics (~65–45 Ma), the effusive products of the Transhimalayan magmatic
297 activity in the southern Lhasa terrane, consist of an east-west linear belt of calc-alkaline andesitic
298 flows, tuffs and breccias, dacitic to rhyolitic ignimbrites and hypabyssal rocks (Mo et al., 2008).
299 The southern Lhasa terrane also includes younger Cenozoic rocks: potassium-rich mafic rocks (23–8
300 Ma, Guo et al., 2013) and adakites (30–9 Ma, Chung et al., 2009), that are coeval with Himalayan
301 leucogranites and migmatites (24–15 Ma, Searle et al., 2010; 25–9 Ma, Guo and Wilson, 2012). These
302 rocks are of limited extent compared to the Transhimalayan Arc rocks.

303 The Indian plate, comprising the Himalayan thrust belt south of the suture zone, mainly
304 consists of metasedimentary rocks of Proterozoic and Paleozoic–Eocene (Tethyan) age, with GH
305 rocks having been metamorphosed to amphibolite-granulite facies in the Oligocene-Miocene (Kohn,
306 2014) since India-Asia collision ~ 50 Ma (Najman et al., 2010). (Meta-) sedimentary rocks from TH,

307 GH and LH in the eastern Himalayan region yield U-Pb zircon dates older than ca. 200, 700 and 900
308 Ma, respectively (Aikman et al., 2008; Webb et al., 2013). U-Pb age spectra of detrital TH and GH
309 zircons across the Himalayan orogen exhibit main peaks at ~0.5 and 0.8–1.2 Ga, while in LH spectra
310 the dominant age range is 1.7 to 2.0 Ga (Parrish and Hodges, 1996; DeCelles et al., 2000; McQuarrie
311 et al., 2008; Gehrels et al., 2011; Martin et al., 2011), although zircon grains as young as 0.5 Ma occur
312 in the outer LH (Myrow et al., 2003; McKenzie et al., 2011; Gehrels et al., 2011). U-Pb zircon dates
313 younger than 50 Ma in Paleogene granitoids (e.g. 44 Ma, Aikman et al., 2008; 42–43 Ma, Zeng et al.,
314 2011; 47–30 Ma, Hou et al., 2012) and migmatites (31–17 Ma, Rubatto et al., 2012) intruding the
315 eastern TH and GH testify to a prolonged Eocene-Oligocene phase of crustal melting within the
316 Himalayan orogen. In the Himalaya south of the suture zone, Cretaceous–Paleogene plutonic rocks (in
317 the range ~50–75 Ma) are absent, therefore first evidence of the Asian Transhimalayan Arc detrital
318 material in the Surma Basin constrains the occurrence and timing of river capture.

319 First we provide U-Pb detrital evidence consistent with river capture of the Yarlung Tsangpo
320 by the Brahmaputra River, documented by arrival in the Surma Basin of Cretaceous–Paleogene
321 zircons (Fig. 2) with predominantly oscillatory zoning typical of volcanic-plutonic rocks derived from
322 the erosion of the Transhimalayan Arc. In addition to zircon U-Pb single grain dating, we report the
323 first published single grain U-Pb dates of detrital rutile from Himalayan-derived deposits of the
324 Bengal Basin and from modern rivers draining the Transhimalayan Arc and Himalaya of the Indian
325 plate. Detrital zircons from modern rivers are used to characterise potential rock sources (Fig. 3).



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Fig. 3. Detrital U-Pb data of modern river sands from this study (Supplemental Tables S2 and S4) plotted as relative probability and frequency plots. One zircon sample and four rutile samples are from Henderson et al. (2010) and Bracciali et al (2013), respectively. Sample locations (A–I and Z) as shown in Fig. 1; horizontal axes, percentages and n as in Fig. 2. Concordia diagrams are in Supplemental Fig. S3. Light and dark grey bands, plotted for comparison, represent the main age peaks of detrital zircons in TH, GH, and LH based on literature data; dashed vertical lines indicate the youngest populations generally found in the same formations in the Eastern Himalaya (see text for references).

336 U-Pb dates from single detrital zircons represent high-T igneous and metamorphic events in
337 the source regions, while rutile, a medium-T chronometer, tracks mainly the time of cooling through
338 ~500°C (Bracciali et al., 2013). The two chronometers applied to the same sample provide key
339 complementary information about the thermal events in the source region. Importantly, we use CL
340 imaging to identify and date all zircon growth zones of single grains with a novel approach to dating
341 also very thin (<5 µm) rims. These zircon rims record the latest growth events that otherwise would be
342 missed due to the difficulty in analysing such narrow zones of zircon.

343 Fig. 3 characterises the isotopic zircon and rutile ages from the potential sources to the Bengal
344 Basin as documented in modern fluvial sediments eroded from the eastern Himalaya of the Indian
345 plate. Samples C-G mainly draining GH in Bhutan are characterised by up to 20% of zircon grains
346 (core and rims) and metamorphic rims 20–40 Ma old and by 10–20 Ma rutiles, documenting
347 Himalayan metamorphism and anatexis (Hodges, 2000). The same samples include zircons older than
348 ~500 Ma with a distinct peak around 480–500 Ma, the reported age of granitic gneisses and granites
349 intruding GH that corresponds to the intrusion of late Pan-African granites (Gehrels et al., 2003;
350 DeCelles et al., 2004; Cawood et al., 2007; Gehrels et al., 2011). The 500 Ma peak also characterises
351 TH and GH as shown by detrital U-Pb published data (Fig. 3). The Burhi Dihing (sample H), an
352 eastern tributary of the Brahmaputra that drains the outer part of the Indo-Burman Ranges, is mainly
353 characterised by > 500 Ma zircons, with a prominent peak at ~ 1 Ga (sample H), while the more
354 southern Dhansiri River (sample I) yields a scatter of Mesozoic and Cenozoic as well as > 500 Ma
355 zircons, and two main rutile age populations at 20–30 Ma and ~ 500 Ma. Modern detritus of rivers
356 that drain the Shillong Plateau (samples M and L in Fig. 1; data in Najman et al., 2008) yields only
357 Cambrian and Precambrian zircons, with main peaks around 500 Ma and 1.0, 1.2 and 1.6 Ga. The
358 same Precambrian peaks are found in sandstones of the Proterozoic Shillong Group that are intruded
359 by a 480–500 Ma granite (Yin et al., 2010b).

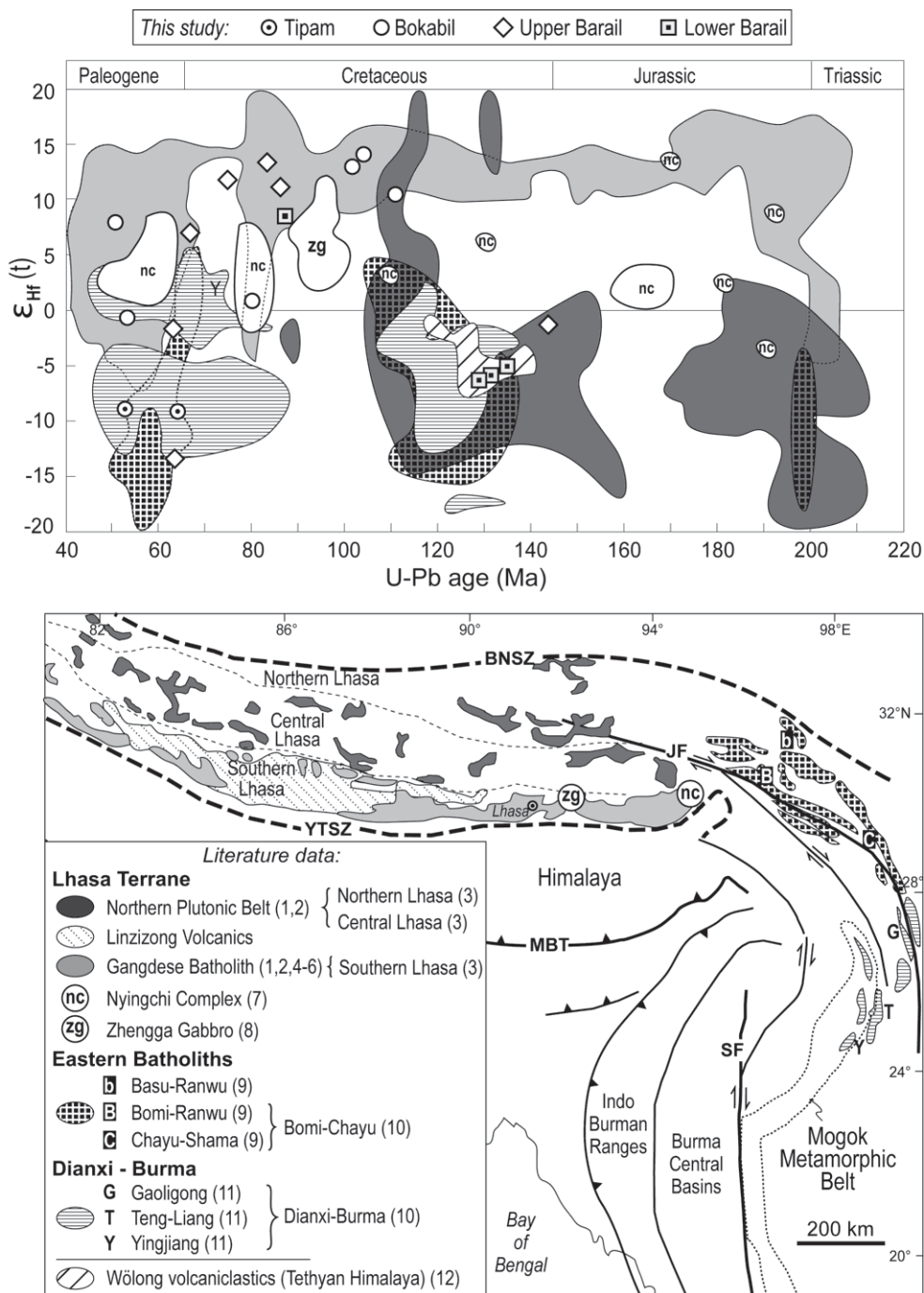
360 By contrast, the Transhimalayan Arc of the Asian plate (samples A and B) is mainly
361 characterised by zircon U-Pb dates between 50–75 Ma reflecting derivation from pre-collisional
362 subduction-related granitoids, while rutile in this age range or younger is minimal or lacking, with

363 grains exclusively (sample B) or mainly (sample A) 100–200 Ma. The detrital age pattern of the
364 Brahmaputra (sample Z) includes all the different components described above.

365 In the Surma Basin all zircon samples are characterised by a Cambrian-Ordovician peak (~
366 500 Ma) and by a spread of older ages (Fig. 2). In samples 4 and 7, the lowermost and middle Barail
367 samples, a distinct cluster of ~ 1 Ga zircon is present and rutiles are > 400 Ma (Fig.2). The uppermost
368 Barail sample (8; Fig. 2) is the oldest sample to show both Cenozoic-aged detrital zircon rims and
369 rutiles derived from the exhumed metamorphosed core of the Himalaya and 50–75 Ma old zircons
370 characteristic of Transhimalayan igneous input; the latter is further supported by Paleogene-
371 Cretaceous zircon grains with a positive ϵ_{Hf} isotopic composition which is characteristic from the
372 uppermost Barail sample onwards and consistent with Transhimalayan Arc provenance (Gangdese
373 Batholith, Fig. 4). Such a positive ϵ_{Hf} signature (also typical of the modern Yarlung Tsangpo main
374 trunk; Zhang et al., 2012) contrasts with the generally negative ϵ_{Hf} values of the Northern Plutonic
375 Belt, the Eastern Batholiths and the Dianxi-Burma Batholiths (Fig. 4). Some igneous rocks in Burma
376 are characterised by ~50–80 Ma zircons with slightly positive (<5) ϵ_{Hf} values (the western Yingjiang
377 batholiths of Xu et al., 2012; Y in the diagram of our Fig. 4), hence derivation of some of the Surma
378 Basin zircons from these sources cannot be ruled out. However, the positive ϵ_{Hf} values of most of the
379 Cretaceous–Paleogene zircons from our samples lend support to our interpretation of the
380 Transhimalayan Arc as the dominant igneous source to the Surma Basin.

381 Importantly, the youngest detrital rutile U-Pb, mica Ar-Ar and zircon fission track dates of
382 the uppermost Barail sample overlap within analytical error, being respectively 24.4 ± 2.9 (this work),
383 21.1 ± 3.2 and 23 ± 2 Ma (the latter is the youngest age component of the sample; Najman et al.,
384 2008). Under the assumption of erosion of these different mineral grains from a common source area,
385 these data indicate rapid cooling of the source through ~500–200 °C, hence the depositional age of
386 our uppermost Barail sample is expected to be not much younger than the cooling age of its detrital
387 components (Early Miocene). Rapid orogenic exhumation consistent with progressive erosion to
388 deeper levels of the southern flanks of the Himalayan orogen is observed in the whole Barail
389 formation, as evidenced for example by the short lag time between sediment depositional age of the

390 lowest Barail (38 Ma, biostratigraphic age) and the fission track date of the youngest detrital zircon
 391 population (37 ± 2 Ma) from a sample a few tens m above (Najman et al., 2008).
 392



393
 394 Fig. 4. Plots of initial ϵ_{Hf} versus U-Pb data of selected zircon samples from the Surma Basin
 395 compared to potential bedrock igneous sources from the Himalayan-Tibet-Burma region. (1)
 396 Chu et al. (2006); (2) Zhang et al. (2007); (3) Zhu et al. (2011); (4) Chu et al. (2011); (5) Ji et
 397 al. (2009); (6) Ji et al. (2012); (7) Guo et al. (2011); (8) Ma et al. (2013); (9) Chiu et al.

398 (2009); (10) Liang et al. (2008); (11) Xu et al. (2012). The main geological elements of the
399 region and the location of the igneous rocks are schematically represented on the map
400 (redrawn after Searle et al., 2007; Chiu et al., 2009; Chu et al., 2011; Zhu et al., 2011).
401 Detrital Cretaceous-Paleogene zircons from the Surma Basin characterised by positive initial
402 ϵ_{Hf} values are consistent with derivation from Asian plate (“Lhasa Terrane”), with most grains
403 overlapping with values typical of the Cenozoic Gangdese Batholith. One negative Cretaceous
404 grain in the upper Barail is compatible with derivation from the Northern Plutonic Belt and
405 three lower Barail 130–145 Ma negative grains are compatible with either the Northern
406 Plutonic Belt, the Eastern Batholiths or recycling of Tibetan TH deposits such as the Wölong
407 volcanics (Hu et al., 2010, reference 12). The Gangdese, the Eastern Himalayan or the
408 Dianxi Burma Batholiths might have sourced the Paleogene zircons with a negative ϵ_{Hf}
409 signature. BNSZ: Bangong-Nujang Suture Zone; YTSZ: Yarlung Tsangpo Suture Zone;
410 MBT: Main Boundary Thrust; JF: Jiali Fault; SF: Sagaing Fault. Northern, Central and
411 Southern Lhasa according to Zhu et al. (2011).

412

413

414 Samples 7 and 4 from the middle and lower Barail (Fig. 2), and the underlying Eocene Kopili
415 Formation (Najman et al., 2008) lack 50–75 Ma grains but contain a few grains ~87 and 115–135 Ma,
416 the latter identical to the Tethyan Wölong volcanoclastic rocks (Hu et al., 2010) that are part of the
417 Indian plate south of the suture (see the Hf isotopic composition of three of these lower Barail grains
418 in Fig. 4). Intraplate basaltic rocks in Eastern India such as the Rajmahal and Sylhet Traps (Baksi,
419 1995) have been indicated as potential sources to the Wölong volcanoclastics (Hu et al., 2010). The
420 Sylhet Traps in northeastern India could have also been a primary source of detritus for the lower
421 Barail Formation.

422 The contrast between the lower–middle Barail samples (dominated by Precambrian to
423 Cambrian zircon and rutile grains and total lack of 50–75 Ma zircons) and the overlying samples (with
424 increasingly dominant and upwards-younging Late Cretaceous–Cenozoic zircon and Cenozoic rutile
425 populations, Fig. 2) indicates a major change in provenance which we interpret as resulting from the

426 the river capture of the Yarlung Tsangpo by the Brahmaputra River. This potentially occurred via the
427 transient capture of one or more transverse Himalayan rivers as discussed later in this section. The
428 capture must have taken place prior to the deposition of our uppermost Barail sample, the first to show
429 the Transhimalayan Arc provenance signature and whose stratigraphic age is likely not much younger
430 than 21-18 Ma as discussed earlier in this section. Our data thus constrain the first arrival of
431 Transhimalayan material into the Surma Basin. This was accompanied by enhanced input from the
432 metamorphosed Himalaya (as evidenced from appearance of Cenozoic rutiles) when the GH high
433 grade metamorphic rocks began to be eroded since ca 23–20 Ma (Hodges, 2000). The continuation in
434 the trend of youngest rutile and zircon U-Pb dates upsection reflects continued exhumation to
435 progressively deeper levels of the Himalayan source region, thus ruling out recycling as a major
436 process contributing sediment to the Surma Basin.

437 The petrographic composition of the Surma Basin sandstones since the Early Miocene (upper
438 Barail to Dupi Tila; Fig. 5) indicates gradual relative decrease of quartz and increase upsection of
439 feldspar and lithic grains (cf. Fig. 5A and Fig. 5B). The same samples show a shift from a composition
440 dominated by sedimentary to low-rank metamorphic lithic grains in the lower–middle Barail (Fig. 5D)
441 to a composition more enriched in volcanic to low-rank metavolcanic and medium- to high-rank
442 metamorphic lithic grains in upper Barail to Dupi Tila deposits (Fig. 5C).

443 This general increase upsection in feldspar suggests an increasing contribution from crustal
444 rock sources possibly including an arc terrane. Parallel to the increase of feldspar and lithic grains
445 content is the increase of the Metamorphic Index (MI) of the samples (Fig. 6; Garzanti and Vezzoli,
446 2003). We interpret the increase in MI to reflect progressive erosion into deeper-seated metamorphic
447 units of the growing Himalayan since the Early Miocene (upper Barail time). The contribution from
448 mid-crustal rocks is however less extensive than in modern Brahmaputra sands, characterised by a
449 higher MI (Fig. 6A). This reflects a composition dominated by the erosion of the high grade
450 metamorphic rocks of the eastern syntaxis (accounting for ~ 40% of the total modern Brahmaputra
451 sediment flux, e.g. Garzanti et al., 2004).

452

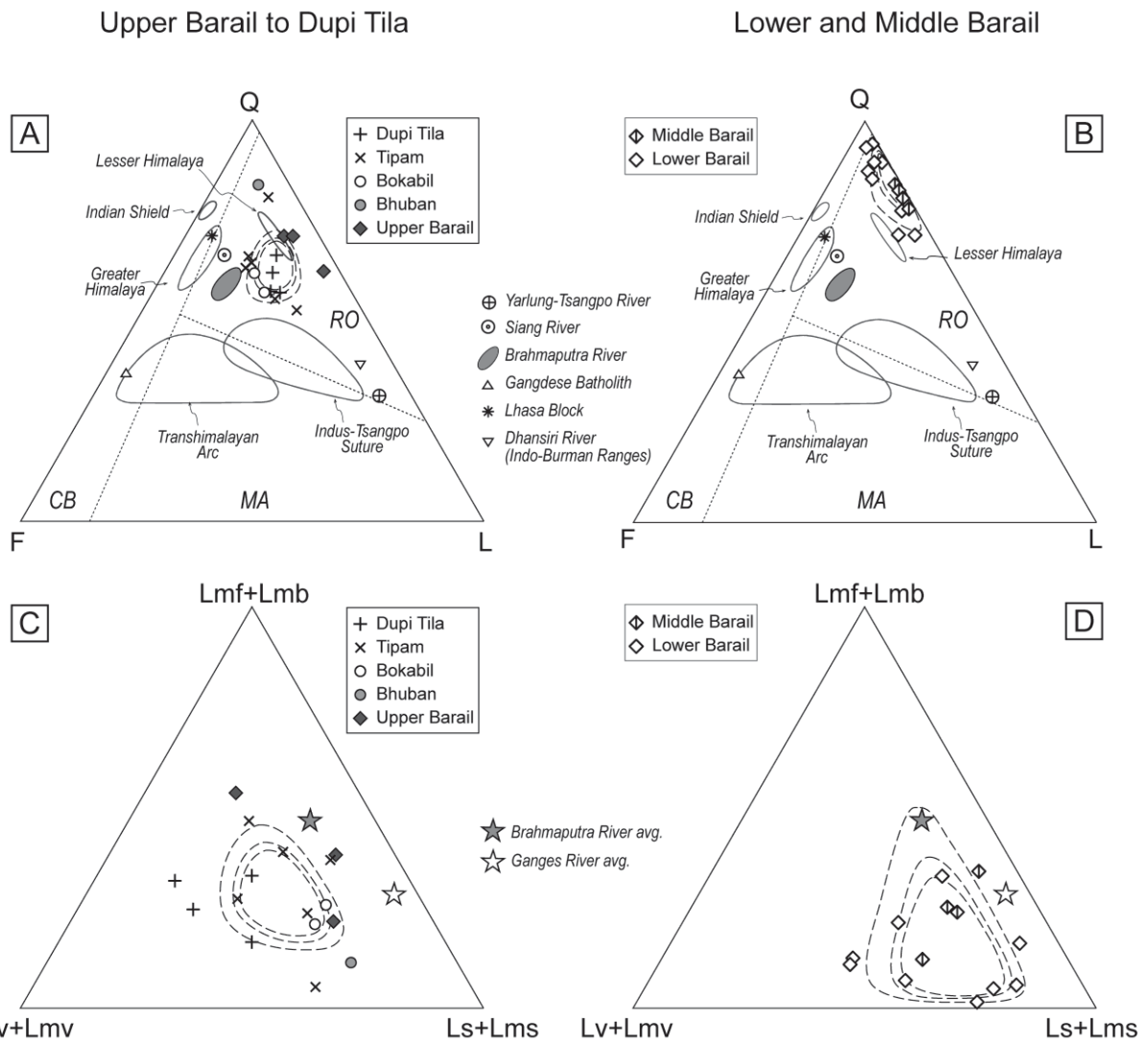


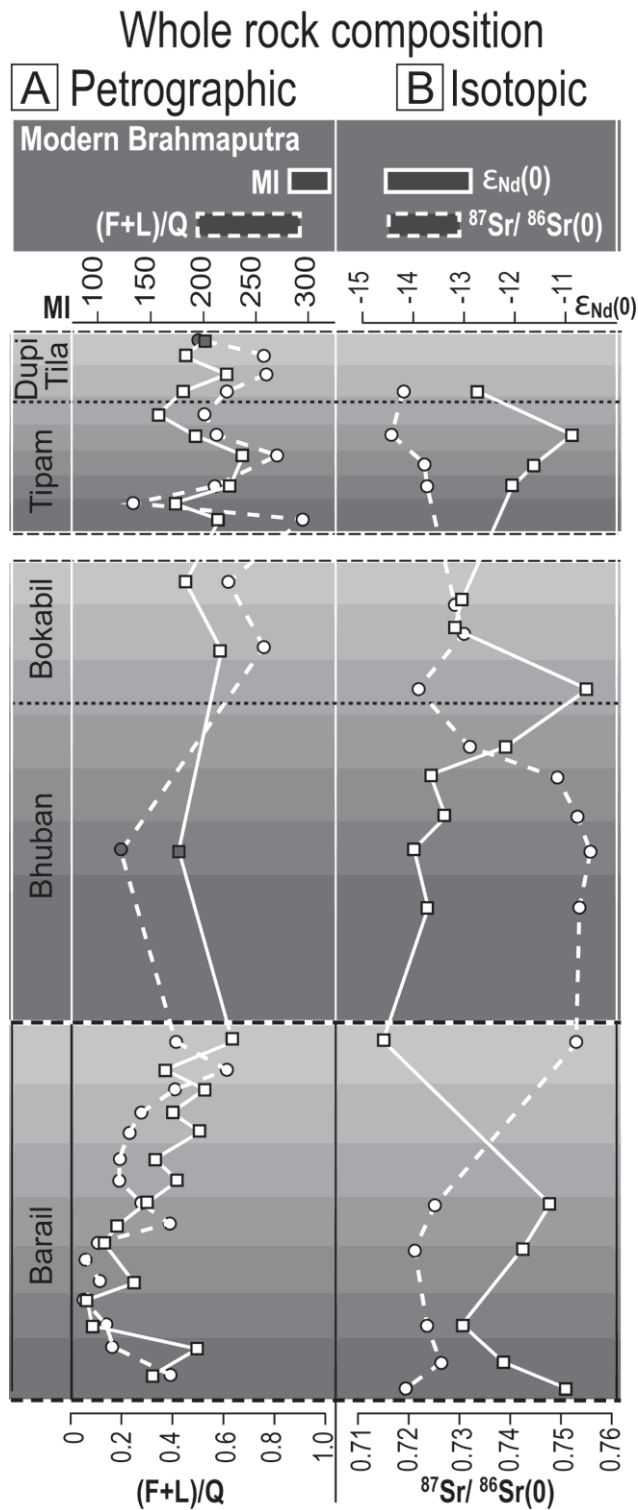
Fig. 5. Modal petrographic data of sandstones from the Surma Basin.

455 A) and B): Surma Basin sandstones (Supplemental Table S6; Barail data from Najman et al.,
 456 2008) plotted on the Q-F-L (total quartzose grains, feldspar grains, lithic grains) ternary
 457 diagram (Dickinson, 1982). All samples (carbonate-free feldspathic lithoarenites based on the
 458 nomenclature of Dickinson, 1982, variably affected by weathering) plot in the Recycled
 459 Orogen (RO) compositional field. CB: continental block; MA: Magmatic Arc. The sand
 460 compositions of the Yarlung Tsangpo, Siang, Brahmaputra and other Himalayan Rivers are
 461 plotted for comparison (Q-F-(L-Lc) data from Garzanti et al., 2004).

462 C) and D): same samples plotted on the (Lmf+Lmb)-(Lv+Lmv)-(Ls+Lms) diagram.
 463 The composition of upper Barail sandstones (lithic arenites) is more similar to the other
 464 Neogene samples than to middle and lower Barail samples (sublitharenites to quartz-arenites).

465 To highlight these differences 90, 95 and 99% confidence regions about the mean (dashed
 466 curves, calculated using the software CoDaPac, Comas-Cufí and Thió-Henestrosa, 2011) are
 467 shown for the two groups of samples (upper Barail-Dupi Tila and lower-middle Barail).

468



469

470 Fig. 6. Overview of petrographic and whole rock isotopic composition of sedimentary
471 samples from the Surma Basin.

472 A) The ratio (Feldspar+Lithic fragments)/Quartz (dashed line) and the Metamorphic Index of
473 sandstones are plotted (Barail petrographic data from Najman et al., 2008). Thick bars:
474 modern Brahmaputra range of values (Garzanti et al., 2004). The stratigraphic position of two
475 samples (dark filled symbols) is not known with respect to the other samples from the same
476 formation.

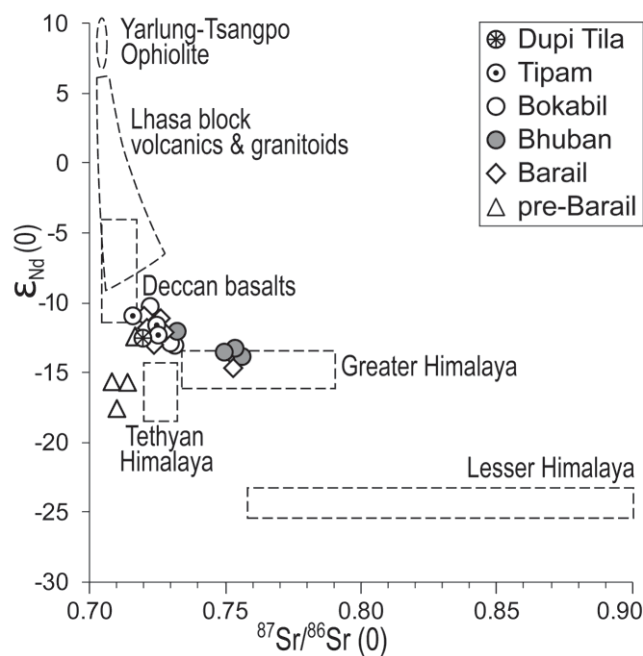
477 B) Whole rock Sr-Nd composition of sandstone and mudstone samples from the Surma Basin.
478 Sr data: dashed line. Thick bars: modern Brahmaputra range of values (Singh and France-
479 Lanord, 2002).

480
481 Whole rock Sr–Nd isotopic data mimic the compositional changes shown by the petrographic
482 data (Fig. 6B and Fig. 7). Overall, the Barail to Dupi Tila samples are characterised by Sr and Nd
483 isotopic compositions that can result from the mixing of different proportions of end-member
484 compositions from the Tibet-Himalaya region (Fig. 7).

485 Five Lower-Mid Barail samples (Fig. 6B) have a rather homogeneous isotopic signature (0.72
486 to 0.73 and -11 to -13). The $^{87}\text{Sr}/^{86}\text{Sr}(0)$ and $\epsilon_{\text{Nd}}(0)$ signature of these samples is interpreted as
487 predominantly TH- and GH-derived (Fig. 7) and is consistent with the composition of Himalayan-
488 derived Eocene rocks of the foreland basin in Nepal (e.g. Robinson et al., 2001). The uppermost Barail
489 sample starts a new trend characterised by a progressive shift through time towards modern
490 Brahmaputra values (Fig. 6B). This sample is characterised by more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}(0)$ ratios
491 coupled to more negative $\epsilon_{\text{Nd}}(0)$ values than the underlying Barail samples (~ 0.75 and -14, Fig. 6B;
492 note that this is the same uppermost Barail sample, number 8, shown in Fig. 2). Consistent with our
493 interpretations from the U-Pb data (Fig. 2) and the petrographic data (Fig. 6A), we interpret this sharp
494 change at the Early Miocene as the result of the accelerated erosional unroofing of older mid-crustal
495 GH metamorphic rocks (Hodges et al., 1996). Further erosion of GH rocks (typical $^{87}\text{Sr}/^{86}\text{Sr}(0)$ and
496 $\epsilon_{\text{Nd}}(0)$ values: 0.76 and -15; Singh and France-Lanord, 2002) coupled to addition of detritus from the

497 LH (the Himalayan source with the most extreme isotopic signature with typical $^{87}\text{Sr}/^{86}\text{Sr}(0)$ and
 498 $\epsilon_{\text{Nd}}(0)$ values = 0.85 and -24, Fig. 7) following its exhumation since the Middle-Late Miocene
 499 (Najman et al., 2009) should have resulted in an increasingly more radiogenic Sr composition and
 500 more negative $\epsilon_{\text{Nd}}(0)$ values of the samples upsection into the Neogene. However, the progressive shift
 501 towards present-day Brahmaputra values (Fig. 6B) from upper Barail times onwards indicates that
 502 such an input (from GH and LH rocks) must have been significantly buffered by mixing with a source
 503 characterised by less radiogenic Sr values and higher $\epsilon_{\text{Nd}}(0)$ values, which we identify as the
 504 Transhimalayan Arc (e.g. $^{87}\text{Sr}/^{86}\text{Sr}(0) < 0.73$ $\epsilon_{\text{Nd}}(0) = -10$ to $+5$; Singh and France-Lanord, 2002;
 505 Lhasa block volcanics and granitoids in Fig. 7) and suture zone ophiolites (Yarlung Tsangpo Ophiolite
 506 in Fig. 7). Such a juvenile component indeed differentiates the modern Brahmaputra (main trunk)
 507 isotopic composition ($^{87}\text{Sr}/^{86}\text{Sr}(0) = 0.71\text{--}0.72$ and $\epsilon_{\text{Nd}}(0) = -14$ to -12 ; Singh and France-Lanord,
 508 2002; Fig. 6B) from the Ganges River ($^{87}\text{Sr}/^{86}\text{Sr}(0) = 0.74\text{--}0.84$ and $\epsilon_{\text{Nd}}(0) = -25$ to -15 ; Singh et al.,
 509 2008) that mainly drains GH.

510



511

512 Fig. 7. Whole rock Sr and Nd isotopic data from the Surma Basin.

513 In this ϵ_{Nd} vs $^{87}\text{Sr}/^{86}\text{Sr}$ diagram Surma Basin samples from this study (Supplemental Table S7)
 514 and pre- Barail samples from Najman et al. (2008) are plotted along with compositional fields

515 of potential source rocks from the Himalaya-Tibet region (Singh et al., 2008; Wu et al., 2010).
516 The main lithotectonic units of the Himalaya have quite distinct Sr-Nd signatures that are
517 reflected in their erosion products (Singh and France-Lanord, 2002; Parrish and Hodges,
518 1996; Robinson et al, 2001; Singh et al., 2008; Wu et al., 2010; Galy et al., 2010).

519
520 As summarised in the Introduction, considerable debate has existed as to whether the Yarlung
521 Tsangpo–Brahmaputra paleodrainage was antecedent to orogenesis, or whether the Yarlung Tsangpo
522 originally flowed east, sequentially captured by rivers such as the paleo-Red, Irrawaddy and Lohit
523 Rivers, before its final capture by the Brahmaputra. All of the data and interpretations presented in this
524 paper are consistent with Early Miocene capture by the Brahmaputra of a river draining the Asian
525 plate, followed by increased exhumation of GH accompanied by significant input from the
526 Transhimalayan Arc.

527 Such a dramatic drainage reorganisation occurred either directly via the Siang as in the
528 modern drainage configuration, or involved the sequential capture of one (or more) transverse
529 Himalayan rivers that, differently from the modern ones that drain only the southern slopes of the
530 Himalayan orogen (e.g. the Subansiri, Fig. 1), would have reached the Transhimalayan Arc to the
531 north of the suture. Our detrital data from the paleo-Brahmaputra deposits in the Surma Basin indicate
532 an enduring and stable detrital signature following the establishment of the drainage in the Early
533 Miocene, testifying to significant and increasing erosion of the Asian arc source and high grade
534 Himalayan metamorphic rocks as a major drainage would have provided. The *capture* (Bishop, 1995)
535 of the Yarlung Tsangpo by the Brahmaputra via the Siang, with integration of the highly elevated
536 Yarlung Tsangpo catchment into the Siang–Brahmaputra drainage basin and preservation of its
537 drainage lines, would explain the peculiar drainage configuration in the eastern syntaxis area (Fig. 1),
538 with the sharp bend of the river representing the elbow of capture (although the current river drainage
539 pattern in the Namche Barwa area has also probably been affected to a certain extent by the
540 deformation associated with the development of the syntaxis). However, based on our data, it is
541 difficult to establish if the connection between the Yarlung Tsangpo and the Brahmaputra occurred via

542 the capture of one or more transverse rivers in sequence, as the switch between these rivers, draining
543 similar geological units, would likely have occurred without major perturbation of the detrital
544 signature we observe in the Surma Basin.

545 Our interpretation of the establishment of the Yarlung Tsangpo–Brahmaputra River in the
546 Early Miocene is strengthened by its consistency with recent provenance studies which utilised
547 detrital zircon U-Pb data from Central Myanmar and Himalayan foreland basins to track the
548 occurrence of detritus from the Yarlung Tsangpo suture zone. Robinson et al. (2014) proposed that an
549 ancestral Yarlung Tsangpo flowed into the Irrawaddy drainage in Central Myanmar until 18 Ma,
550 based on a study which showed the Yarlung Tsangpo suture zone signal was lost from the Irrawaddy
551 basin at that time. This is consistent with the work of Rüber et al (2004) who showed clade divergence
552 of fresh water fish species between the Yarlung Tsangpo and the Irrawaddy regions in the Early
553 Miocene, interpreted to have resulted from a vicariant event, consistent with the palaeodrainage
554 scenario proposed here.

555 Transhimalayan Arc provenance has been observed in the Arunachal Pradesh part of the
556 Siwalik Group foreland basin in sediments of latest Miocene age (~ 7 Ma), just north of the Shillong
557 Plateau by Cina et al (2009) and Chirouze et al (2012a). This was interpreted as the result of capture
558 of the Yarlung Tsangpo first by the Subansiri River and then by the Siang (Cina et al., 2009) or as the
559 result of surface uplift of the Shillong plateau that pushed the paleo-Yarlung Tsangpo–Brahmaputra,
560 already flowing along the Brahmaputra valley as currently located, north towards the Himalayan front
561 at this time (Chirouze et al., 2012a). More recently, Lang and Huntington (2014) recorded Asian-
562 derived detritus in foreland basin Lower Siwaliks deposits which are generally
563 magnetostratigraphically dated from 10 to 14 Ma, with the transition from Lower to Middle Siwaliks
564 also reported at ~8Ma (Ojha et al., 2009). The age of the stratigraphic section of Lang and Huntington
565 at Likabali, lacking any direct age constraint, is inferred based on correlation to the Kameng River
566 section exposed ~250 Km to the SW, where the Lower Siwaliks sedimentary record extends to ca. 13
567 Ma due to basal truncation by the Tipi Thrust (Chirouze et al. 2012b). The data of Lang and
568 Huntington (2014) thus suggest the existence of a paleo-Yarlung Tsangpo–Brahmaputra by at least the
569 upper part of Middle Miocene times (note: not Early Miocene as they wrote). As a whole, the work of

570 Cina et al (2009), Chirouze et al (2012a) and Lang and Huntington (2014) is compatible with a paleo-
571 Yarlung Tsangpo–Brahmaputra flowing along the foreland of the Himalayas at least by 7-13 Ma. This
572 is in agreement with the Sr-Nd-Os isotopic composition of sediment deposited in the last 12 Ma in the
573 Bengal Fan, testifying to a stable erosion pattern in the Himalaya and requiring a stable connection
574 between the Tibetan Plateau and the Bengal Fan such as the Yarlung Tsangpo–Brahmaputra would
575 have provided (Galy et al., 2010). All of these data are consistent with our findings of a Yarlung
576 Tsangpo–Brahmaputra established since the Early Miocene.

577 **6. Conclusions and wider implications**

578 We interpret various changes in provenance in Surma Basin sediments that occurred in the
579 Early Miocene to represent the first arrival of material from the Asian plate, due to river capture of the
580 Yarlung Tsangpo by the Brahmaputra at this time. This river capture may have been caused by an
581 increase in river gradient and stream power due to uplift of the Tibetan plateau, as for example
582 suggested by the numerical modelling of Stüwe et al (2008). It has also been proposed that rapid
583 downcutting of the river may have resulted in the anomalously young metamorphism and recent rapid
584 exhumation of the Namche Barwa syntaxis. In the “tectonic aneurysm” model, the metamorphic
585 massifs at the western and eastern Himalayan syntaxes are created by local feedback between
586 tectonics and erosion; large-magnitude river incisions (by the Indus River which cuts across the
587 western syntaxis and the Yarlung Tsangpo–Brahmaputra which cuts across the eastern syntaxis) focus
588 deformation of weak crust, leading to lower crustal flow into the region. This creates a self-sustained
589 failure of a normally strong boundary and rapid exhumation (Zeitler et al., 2014, and references
590 therein). The Yarlung Tsangpo river capture has been proposed as the trigger for the tectonic
591 aneurysm (Zeitler et al., 2001b; see also Robl et al., 2008). However, our data show that capture is at
592 least 10 Ma older, and thus if such capture was routed through the Siang, it refutes the river capture as
593 the trigger for the tectonic aneurysm, in agreement with the recent research of Wang et al (2014).
594

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603 **Appendix A. Supplementary Material**

604 Supplementary material related to this article can be found online at
605 <http://dx.doi.org/101016/j.epsl.xxxx.xx.xxx>.

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