

## When did the Indus River take on its "modern" drainage configuration?

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### Abstract:

In order for sedimentary archives to be used as a record of hinterland evolution, the factors affecting the archive must be known. In addition to tectonics, a number of factors such as changes in climate and palaeo-drainage, as well as the degree of diagenesis, influence basin sediments. The Indus River-delta-fan system records a history of Himalayan evolution, and both the onshore and offshore sedimentary repositories have been extensively studied to research orogenesis. However, a number of unknowns remain with regards to this system. This paper seeks to elucidate the palaeodrainage of the Indus River, in particular when it took on its modern drainage configuration with respect to conjoinment of the main Himalayan (Punjabi) tributary system with the trunk Indus River. We leverage the fact that the Punjabi tributary system has a significantly different provenance signature to the main trunk Indus, draining mainly the Indian plate. Therefore, after the time when the Punjabi tributary system joined the main trunk Indus, the proportion of Indian plate material in the repositories downstream of the confluence should have a higher proportion of Indian plate material compared to the upstream repository. We compared bulk Sr-Nd data and detrital zircon U-Pb data from the Cenozoic upstream peripheral foreland basin and downstream Indus delta and Indus Fan repositories. We determined that repositories below the confluence had a higher proportion of Indian plate material compared to repositories above the confluence, throughout Neogene times. We therefore conclude that the Indus River took on its current configuration with the Punjabi tributary system draining into the Indus trunk river in the Paleogene, early in the history of the orogen: Pinpointing the exact time when the tributary system joined the Indus should be determinable from a shift to more Indian plate input in the downstream repositories only. Whilst the upstream repository records no change in Indian plate input from Eocene to Neogene times, a shift to increased Indian plate material occurs at the Eocene-Oligocene boundary in the delta but sometime between 50-40 Ma in the fan. Further work is therefore required to understand the discrepancy between the two downstream repositories but nevertheless we can conclude that the tributary system joined the trunk Indus at or before the start of the Oligocene.

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38 **Keywords:** Himalaya; Indus River; provenance; Sr-Nd analyses, zircon U-Pb analyses, mica Ar-Ar  
39 analyses.

40

## 41 **1. Introduction**

42 The Himalaya, as the largest orogen on Earth, garners significant interest from researchers in a variety of  
43 disciplines. Whilst considerable information on the mountain belt's evolution can be determined from  
44 its hard rock geology, its early history is often destroyed in these rocks by later tectonism,  
45 metamorphism and/or erosion. In these circumstances, researchers turn to information recorded in the  
46 sediment archive of material eroded from the mountain belt and preserved in surrounding sedimentary  
47 basins, both onshore and offshore.

48 The main repositories of Himalayan detritus are preserved in the orogen's suture zone , peripheral and  
49 axial foreland basins onshore (e.g. Hodges 2000, Najman 2006, Shah 2009), and the Indus and Bengal  
50 Fans offshore, which are the world's largest sediment fans (Nyberg et al., 2018). Detritus from all these  
51 basins has been studied to document hinterland evolution, using a variety of bulk rock and single grain  
52 analytical techniques. For example, studies of the Indus River's sedimentary repository include detrital  
53 feldspar Pb isotopic analyses applied to the Indus suture zone molasse (Clift et al., 2001b), detrital zircon  
54 fission track and Sm-Nd bulk analyses have been applied to the peripheral foreland basin sedimentary  
55 rocks (e.g., Chirouze et al., 2015), detrital zircon U-Pb analyses have been applied to the axial foreland  
56 basin (e.g., Zhuang et al., 2015) and heavy mineral and petrography (Andò et al., 2020; Garzanti et al.,  
57 2020) data applied to the Indus Fan. However, in order for the sediment archives to be robustly  
58 interpreted, a knowledge of the river's palaeo-drainage evolution must be known, since significant  
59 drainage changes will affect the sediment archive. Reconstruction of the lower Indus palaeo-drainage is  
60 the focus of this paper.

61 Today, the Indus River flows west along the Indus suture zone which separates the Indian and Asian  
62 plates, before turning south across the Himalayas to flow eventually into the northern Indian Ocean,  
63 giving rise to the Indus Fan (Fig. 1). Here we define the Lower Indus as that part of the Indus River  
64 downstream (south) of the Himalayan mountain front, flowing axially, southward along the Indus Basin.  
65 We define the Upper Indus as that part of the Indus River which flows through the mountains, sub-  
66 divided into the "west-flowing axial Upper Indus" which flows from its headwaters, west, axially along  
67 the Indus suture zone, and, further downstream, the "south-flowing transverse Upper Indus", which  
68 cuts south across the mountain range (Fig 1A). The main tributaries to the Indus are the Punjabi or  
69 Himalayan tributaries of the Jhelum, Chenab, Ravi, Beas and Sutlej Rivers, herein called the Punjabi  
70 tributary system, which drain predominantly the Indian plate (Fig 1C).

71 Mid Eocene Owen Ridge sediments are considered to be early Indus Fan material derived from north of  
72 the Indian plate (Clift et al., 2001a; Clift et al., 2002a). This places a lower bound on the timing of  
73 initiation of the Indus River, although its upstream configuration is debated. For the Upper Indus, the  
74 proposed time of its initiation as a river flowing westward along the suture zone ranges from early  
75 Eocene through Miocene (Bhattacharya et al., 2020; Clift et al., 2001b; Henderson et al., 2011; Najman,  
76 2006; Sinclair and Jaffey, 2001).

77 This paper focusses on the palaeodrainage evolution of the Lower Indus River. Various suggestions have  
78 been made regarding whether western Himalayan rivers switched between flowing east to the Ganges  
79 and Bengal Fan catchment and west to the Indus River and Fan catchment. Whilst a number of authors  
80 based their interpretations on palaeocurrent data from the peripheral foreland basin deposits (e.g. see  
81 review in Burbank et al, 1996), Clift and Blusztajn (2005) used geochemical data from the Indus Fan.  
82 They considered that changes in the geochemical signature of the Indus Fan sediment archive after 5 Ma  
83 represented a major drainage change in the Lower Indus at this time, when the Punjab tributaries to the  
84 Lower Indus River (Jhelum, Chenab, Ravi and Sutlej Rivers, Figs. 1A and 1C) switched from flowing east  
85 to the Ganges and Bengal Fan, to west to the Indus River and Indus Fan. However, Chirouze et al. (2015),  
86 considered that this geochemical change could be better interpreted as the result of variations in upland  
87 exhumation. This suggestion was later agreed upon by the original proponents of the drainage diversion  
88 hypothesis (Clift et al. (2019) and Zhou et al. (2021)) and thus the timing when the Indus River took on  
89 its current configuration with respect to the Punjab tributary system remains unknown.

90 Using a similar rationale to Chirouze et al (2015), we compare provenance indicators from upstream and  
91 downstream of the confluence of the Punjab tributary system with the Indus River, and from this  
92 comparison we determine when a provenance change in the downstream repository is detected and  
93 thus when the tributary system joined the trunk Indus. We extend the peripheral foreland basin Sr-Nd

94 dataset of Chirouze et al (2015) from the mid Miocene, down section as far as the Eocene in order to  
95 determine when the provenance change occurred, and additionally we apply new provenance  
96 indicators, namely detrital zircon U-Pb ages and detrital white mica Ar-Ar ages.

97

## 98 **2. Background:**

### 99 ***2.1 Himalayan geology***

#### 100 *2.1.1 Tectonic units*

101 The Indus suture zone separates the Asian Lhasa Terrane to the north from the Indian plate to the  
102 south. In the west, the Kohistan-Ladakh intra-oceanic island arc (KLIA) is sandwiched between the  
103 Indian and Asian plates, with the southern margin of the Asian plate at this location comprised of the  
104 Karakoram and Hindu Kush). The northern suture separating the Asian plate and KLIA is termed the  
105 Shyok Suture Zone and the southern suture separating the KLIA and Indian plate is termed the Indus  
106 Suture zone, also known as the Main Mantle Thrust in this region (Fig. 1C). The Indus River flows west  
107 along the Indus suture zone before turning south to cross the Himalaya and foreland basin before  
108 debouching into the Arabian Sea.

109 The Lhasa terrane comprises Phanerozoic low grade metamorphic and sedimentary cover overlying  
110 Precambrian-Cambrian basement (e.g., Leier et al., 2007). Along its southern rampart are intruded the  
111 Gangdese continental arc batholiths of the Transhimalaya which represent the Andean-type southern  
112 margin of Asia prior to consumption of the intervening Neo-Tethys ocean (Schärer et al., 1984). Whilst  
113 Gangdese intrusions are Mesozoic-Paleogene aged, post-collisional igneous activity continued into  
114 Miocene times (Hodges, 2000). To the west, the Lhasa terrane terminates against the Karakoram Fault.  
115 West of the fault, the southern margin of Asia is represented by the Karakoram (Fig 1C). The Karakoram

116 terrane is divided into three units (Hildebrand et al., 1998; Hildebrand et al., 2001; Searle et al., 1999):  
117 the Northern Karakoram Sedimentary Unit, the Southern Karakoram Metamorphic Belt and the  
118 intervening Karakoram Batholith. The Northern Karakoram Sedimentary Unit comprises pre-Ordovician  
119 crystalline basement covered by an Ordovician to Cretaceous sedimentary succession (Gaetani and  
120 Garzanti, 1991; Gaetani et al., 1993; Zanchi and Gaetani, 2011). The Karakoram Batholith includes pre-  
121 India–Asia collision, Andean-type subduction-related granitoids and post-India–Asia collision  
122 leucogranites. Age of metamorphism of the Southern Karakoram Metamorphic Belt ranges from Late  
123 Cretaceous to late Miocene (Fraser et al., 2001; Palin et al., 2012; Searle et al., 2010).

124 The Kohistan-Ladakh Island arc (KLIA) separates the Indian and Asian plates in the west of the orogen. It  
125 consists of Late Cretaceous and Eocene plutonic belts, and pyroxene granulites, calc-alkaline volcanics,  
126 amphibolites, and minor metasediments (Coward et al., 1984; Schaltegger et al., 2002), fringed by  
127 ophiolitic melange in the southern suture (DiPietro et al., 2000; DiPietro and Pogue, 2004).

128 The Indian plate lies to the south of the KLIA. As summarised in Hodges (2000), In the central and  
129 eastern part of the orogen, the Indian plate Himalaya is divided, from north to south, into the Tethyan  
130 Himalaya, the Greater Himalaya, Lesser Himalaya and Cenozoic foreland basin sedimentary rocks of the  
131 Sub-Himalaya (Fig 1C). Typically, the Tethyan Himalaya, separated from the Greater Himalaya to the  
132 south by the South Tibetan Detachment System, consists of Paleozoic–Mesozoic sedimentary and low-  
133 grade metasedimentary rocks which were deposited on the Tethyan ocean passive margin; the Greater  
134 Himalaya, separated from the Lesser Himalaya to the south by the Main Central Thrust, consists  
135 predominantly of medium- to high-grade Neoproterozoic-Ordovician metamorphic rocks that were  
136 subjected to metamorphism and anatexis during the Cenozoic Himalayan orogeny when they were  
137 intruded by Neogene leucogranites; and the Lesser Himalaya, separated from the Cenozoic Sub-  
138 Himalaya foreland basin sedimentary rocks to the south by the Main Boundary Thrust, consisting of

139 Paleoproterozoic metamorphosed and unmetamorphosed Indian plate rocks. These lithologies also  
140 broadly constitute the Indian plate Himalaya to the west in Pakistan. However, exact correlation is  
141 uncertain, the degree of metamorphism differs, and the lithologies are not structurally imbricated in the  
142 same way (Treloar et al., 2019). According to DiPietro and Pogue (2004), north of the Khairabad Thrust  
143 (MCT equivalent in Pakistan) metamorphosed rocks of ages equivalent to the Tethyan, Greater and  
144 Lesser Himalaya are found, whilst both Lesser and Tethyan equivalents are found between the  
145 Khairabad Thrust and the MBT. The Nanga Parbat syntaxis is considered to be of Lesser, Greater and  
146 Tethyan Himalayan affinity (Argles et al., 2003). In this paper, we refer to the Neoproterozoic-  
147 Ordovician rocks as *Greater Himalayan lithological correlatives*, the Paleoproterozoic rocks as *Lesser*  
148 *Himalayan lithological correlatives*, and the Paleozoic-Mesozoic rocks as *Tethyan Himalaya lithological*  
149 *correlatives*. Such terms do not reflect the location of the rocks within the various thrust-bound  
150 terranes, as they do further east.

151 The units described above have distinct zircon U-Pb ages and Nd isotope signatures associated with  
152 different crustal evolution histories (e.g., Argles et al., 2003; Clift et al., 2019; DeCelles et al., 2004;  
153 DeCelles et al., 2016a; Gehrels et al., 2011; Najman, 2006). These differences, (Table 1), allow for use of  
154 these techniques as provenance indicators in the detrital record downstream (e.g., Clift et al., 2019;  
155 DeCelles et al., 2004; DeCelles et al., 2016a; Gehrels et al., 2011; Najman, 2006).

156 The overwhelming majority of zircons from the Indian plate have U-Pb ages >400 Ma (DeCelles et al.,  
157 2004; Gehrels et al., 2011), with the minor exception of grains dated ~130 Ma from the Tethyan  
158 Himalaya (e.g. Clift et al., 2014) and Neogene grains eroded from leucogranites (e.g. Hodges, 2000 and  
159 references therein). Within the Indian plate, grains 1500-2300 Ma are characteristic of the Lesser  
160 Himalaya, and 300-1250 Ma characteristic of the Greater and Tethyan Himalaya, although not uniquely  
161 so (Clift et al., 2019). By contrast, zircons from the KLIA are exclusively aged 40-200 Ma, whilst the



162 southern Asian margin (the Karakoram and to the east the Lhasa Block) also have a high proportion of  
163 grains of such age, but also with some Neogene grains, and older grains stretching to the Precambrian,  
164 derived from the substrate into which the Mesozoic-Paleogene plutons intruded (e.g. Zhuang et al.,  
165 2018 and references therein).

166 The old continental crust of the Indian plate has a mean  $\epsilon_{\text{Nd}}$  value of -15 for the Greater Himalaya, -22  
167 for the Lesser Himalaya, and -11 for the Tethyan Himalaya (Ahmad et al., 2000; Deniel et al., 1987;  
168 Richards et al., 2005; Robinson et al., 2001; Zhang et al., 2004). By contrast, the Asian and intra-oceanic  
169 arc terranes have more positive values, reflecting the dominance of Mesozoic-Paleogene plutons: the  
170 KLIA has values around +5 (Bignold and Treloar, 2003; Khan et al., 1997; Khan et al., 2004; Khan et al.,  
171 2009), whilst the Karakoram, which consists of both old sedimentary and metamorphic rocks as well as  
172 younger plutons, has an average value around -9.6 (Mahéo et al., 2009; Miller et al., 1999). Data from  
173 the Lhasa Block are mainly from the central and eastern part of the orogen: the Gangdese /  
174 Transhimalaya have values ranging from +0.9 to 5.5 for the Mesozoic granitoids and +2.4-8.5 for the  
175 Paleocene-Eocene granitoids in contrast to the Oligocene-Miocene granitoids with values of -9.4 to 5.5  
176 (Ji et al., 2009; Pan et al., 2014), whilst the continental substrate into which these plutons intruded have  
177 an average recorded  $\epsilon_{\text{Nd}}$  value of -9 (Pan et al., 2014; Zhu et al., 2009; Zhu et al., 2012).

### 178 *2.1.2. Tectonic evolution.*

179 Prior to India-Asia collision, India was subducting beneath Asia as Neo-Tethys closed, with the KLIA  
180 located between the two continents in the west. The timing of India-Asia collision, and whether the  
181 island arc collided with India or Asia first, is disputed; a majority of researchers consider India-Asia  
182 collision occurred around 55-60 Ma (see review in Hu et al., 2016 and references therein) with other  
183 estimates extending to c. 35 Ma or 25-20 Ma (Aitchison et al., 2007; Bouilhol et al., 2013; van  
184 Hinsbergen et al., 2012).

185 The west differs from the better studied east and central part of the orogen in both the presence of the  
186 KLIA, and in the timing of exhumation of the Indian plate. In the west, a tectonic wedge consisting of the  
187 KLIA, ophiolitic melange and thrust slices of Lesser Himalayan and Tethyan correlatives of the Indian  
188 plate was in position and thrust over the Indian plate foreland prior to 47 Ma. Thereafter, Indian plate  
189 Lesser-, Greater- and Tethyan Himalayan correlatives were exhumed from beneath the wedge (DiPietro  
190 et al., 2008), predominantly during the Paleogene with a pulse of deformation also in the earliest  
191 Miocene, ~20 Ma (Argles et al., 2003, and references therein; DiPietro et al., 2021). Substantial rapid  
192 exhumation of the Indian plate hinterland is not recorded after this time, except in the Nanga Parbat  
193 region (Fig 1C), a syntaxis of Lesser, Greater and Tethyan Himalayan lithological correlatives, where  
194 rapidly accelerating exhumation is recorded over the Pliocene (e.g., Schneider et al., 2001). Thrusting  
195 and exhumation propagated south towards the foreland in the mid or late Miocene, continuing into the  
196 Pliocene (Burbank and Tahirkheli, 1985; Yeats and Hussain, 1987).

197 To the north of the Indian plate, moderate exhumation is recorded from Eocene times in the Kohistan  
198 Island arc (Van Der Beek et al., 2009) and by contrast, the Karakoram of the Asian plate records periods  
199 of rapid exhumation around 27-35 Ma, 13-17 Ma, 7-8 Ma and 3.3-7.4 Ma (Dunlap et al., 1998; Wallis et  
200 al., 2016; Zhuang et al., 2018).

## 201 **2.2. Foreland basin geology**

202 In Pakistan, current basinal environments along which the modern Indus River flows, consist of (1) the  
203 peripheral foreland basin that strikes east-west along the southern margin of the orogen, and (2) the  
204 north-south striking Lower Indus axial foreland basin along which the Lower Indus River debouches into  
205 its delta in the Arabian Sea (Fig. 1A).

### 206 **2.2.1 Peripheral foreland basin**

207 Foreland basin stratigraphy is for the most part invariant along strike in the orogen, with local minor  
208 facies variation, although formation names differ. In Pakistan, the Paleogene has a number of formation  
209 names for equivalent units, in different areas (Pivnik and Wells, 1996). We adopt the formation names in  
210 our area of study, which for our Paleogene samples is the Hazara-Kashmir syntaxis (HKS) (Figs. 1A and  
211 B), with the stratigraphy as recorded in Table 1. At this location, the Paleocene Lockhart Limestone is  
212 overlain successively by the latest Paleocene (57-55 Ma) Patala Formation, the early Eocene (55-53 Ma)  
213 Margala Hill and Chorgali Formations, and the early-Mid Eocene (53-43 Ma) Kuldana Formation (Baig  
214 and Munir, 2007; Bossart and Ottiger, 1989; Ding et al., 2016b; Qasim et al., 2018). These formations,  
215 which stretch from marine facies to the transitional Kuldana Formation, are separated from the  
216 overlying continental alluvial facies by a late Eocene-Oligocene unconformity. Above the unconformity,  
217 there is the Murree Formation, also called the Balakot Formation in the HKS. In this syntaxis, the Murree  
218 Formation has a latest Oligocene maximum depositional age (MDA) as determined by the two youngest  
219 zircons within error, with a weighted mean U-Pb age of  $22.6 \pm 1.0$  Ma (this study, section 4.2) from a  
220 sample collected near Paras, north of Balakot (Fig. 1B), supported by a grain dated at  $22.7 \pm 0.4$  Ma  
221 (Ding et al 2016b) from a section 15 kms south at Muzaffarabad (Fig. 1B). South-west of the Hazara-  
222 Kashmir syntaxis, at Murree hill station (MHS) (Fig. 1B), detrital mica Ar-Ar ages indicate an MDA of  $<24$   
223 Ma (this study, section 4.3). These MDAs are in agreement with the early Miocene dating of the Murree  
224 Formation to the south, based on mammal fossils (Shah, 2009). Further south, in the Kohat and Potwar  
225 Plateaus (Fig. 1A) are the alluvial Kamlial Formation and overlying Siwalik Group, subdivided into the  
226 Chinji, Nagri and Dhok Pathan Formations (see Table 1 for stratigraphy). These formations are dated by  
227 magnetostratigraphy (Johnson et al., 1985), at 18-14 Ma, 14-11 Ma, 11-8.5 Ma, and  $<8.5$  Ma,  
228 respectively.

### 229 2.2.2 Lower Indus axial Basin

230 The stratigraphy of the Lower Indus Basin in the Sulaiman and Kirthar regions are broadly correlative  
231 (Shah, 2009). It encompasses the early Eocene Ghazij Formation, the middle-late Eocene Kirthar Group,  
232 the Oligocene-early Miocene Chitarwata Formation, the late Early to middle Miocene Vihowa  
233 Formation, and the middle Miocene-Pliocene rocks of the Siwalik Group (Roddaz et al., 2011; Shah,  
234 2009; Zhuang et al., 2015), as denoted in Table 1. Facies are predominantly marine until the Chitarwata  
235 Formation which transitions up from deltaic to fluvial facies. Fluvial facies then persist until the top of  
236 the section.

### 237 **2.3 Paleodrainage models**

#### 238 *2.3.1 The early drainage configuration of the palaeo-Indus: evidence from the Indus Fan sedimentary* 239 *archive*

240 The oldest eastern Indus Fan sample (IODP 355, U1456 and 1457, Fig 1A) to have been subject to  
241 detrital zircon U-Pb analyses is 15 Ma. This shows evidence of input from the Karakoram (Zhou et al.,  
242 2022), indicating the drainage basin of the palaeo-Indus stretched as far back as the Shyok Suture Zone  
243 by this time (Fig 1C). The oldest sample subjected to detrital zircon U-Pb dating in the western part of  
244 the Indus Fan (ODP 731, Fig 1A) is ~ 30 Ma. This sample shows evidence of input from the KLIA/Asian  
245 plate (undifferentiated), indicating that the river stretched back at least beyond the Indus Suture Zone  
246 (Fig 1C) by that time (Feng et al., 2021). Likewise, Mid Eocene Owen Ridge sediments from DSDP 224  
247 (Fig 1A), considered to be early Indus Fan deposits (Clift et al., 2001a; Clift et al., 2002a), show bulk rock  
248  $\epsilon_{Nd}$  signatures and K-feldspars with Pb isotope compositions indicative of derivation from north of the  
249 Indian plate (Clift et al., 2001a). This indicates that the river's drainage basin stretched back as least as  
250 far as the Indus Suture Zone and KLIA at this time.

#### 251 *2.3.2. The early drainage configuration of the upper axial palaeo-Indus: evidence from the Indus Suture* 252 *Zone molasse.*

253 Clift et al. (2001b) considered that various isotopic provenance datasets and palaeocurrents in Indus  
254 suture zone sedimentary rocks of early Eocene age indicated contribution from the Lhasa Block to the  
255 east, requiring along strike east to west flow along the suture zone at that time. However, Najman  
256 (2006) argued that an alternative source with a suitable signature could potentially be that of the  
257 Karakoram, located north of the suture zone sediments under discussion, and therefore not requiring  
258 along-strike transport and axial flow. Sinclair and Jaffey (2001) considered their facies analyses of the  
259 suture zone sediments indicated internal rather than through-flowing drainage until at least the early  
260 Miocene. Later, Henderson et al. (2010) reported that white micas, interpreted as Indian-plate derived,  
261 first occurred in the same suture sedimentary rocks as Asian-derived zircons, in suture zone sedimentary  
262 rocks dated <23 Ma. From these mixed source sedimentary rocks, and accompanying facies analysis,  
263 they considered the Indus River was flowing in the suture zone at that time. However, it should be noted  
264 that (1) micas were also recorded in older suture zone sedimentary rocks but they were of too small  
265 grain size to analyse, (2) Indian plate material with low muscovite fertility such as from the Tethyan  
266 Himalaya may well have contributed to the suture zone rocks earlier and (3) an open question remains  
267 as to why the first appearance of micas interpreted as Indian-derived, was not also accompanied by an  
268 influx of Paleozoic and older zircons, also typical of the Indian plate. Whilst subsequently, such old  
269 zircons, interpreted as Indian rather than Asian-derived, have been documented in suture zone  
270 sediments as old as ca. 50 Ma (Bhattacharya et al., 2020), nevertheless they are not present in the  
271 samples analysed for white mica Ar-Ar analyses by Henderson et al (2010). Whilst mineral sorting due to  
272 different hydraulic regimes of zircon versus mica (Malusà et al., 2016) might explain the difference, we  
273 suggest that, with the benefit of subsequent better characterisation of the ages of micas from the  
274 southern margin of the Asian plate (Zhuang et al 2018), an Asian Karakoram provenance might provide  
275 an alternative provenance for these micas. Regardless, mixed Indian-Asian provenance, unaccompanied  
276 by facies data indicating deposition in a major river, does not indicate east-west through-flow of

277 drainage. Bhattacharya et al. (2020) demonstrated from provenance data that detritus from the east  
278 was transported west by ca 27 Ma. Thus we may conclude that an axial upper Indus flowed west by  
279 Oligocene times. Prior to that the suture zone was a depocentre, but it may have been externally or  
280 internally drained.

281 *2.3.3. Early drainage configuration of the upper transverse palaeo-Indus River: evidence from the*  
282 *peripheral foreland basin deposits*

283 In the peripheral foreland basin, detrital blue-green hornblende considered to be derived from the KLIA,  
284 is first recorded in the Kohat and Potwar plateaus from 11 Ma (Nagri Formation), interpreted as palaeo-  
285 Indus deposits (Abbasi and Friend, 1989; Cervený and Johnson, 1989). Ullah et al. (2015) applied  
286 geochemistry and petrography to the Chinji Formation (14-11 Ma) to record material from the KLIA and  
287 Indus suture zone. Based on petrography, Najman et al. (2003) recorded arc-derived detritus in the  
288 Potwar plateau from the start of their studied section at 18 Ma, from which they interpreted that this  
289 time represented the first arrival of sediment from the Upper Indus River to the foreland basin in this  
290 region. Still later work (Ding et al., 2016b; Qasim et al., 2018) recorded arc-derived zircons in the  
291 foreland basin latest Paleocene to Early Eocene Margala Hill and uppermost Patala Formations,  
292 indicating derivation from north of the Indus Suture Zone / Main Mantle Thrust since at least 55 Ma.

293 Whilst the above provenance data indicates derivation from material as far north as the KLIA since  
294 Eocene times, whether these rocks represent the deposits of the palaeo-Indus is debated (Cervený et  
295 al., 1989; Willis, 1993; Zaleha, 1997). Chirouze et al (2015) proposed a Lhasa Block origin for detrital  
296 zircons with old fission track ages in the Chinji Formation. This would indicate that the contributing  
297 drainage basin stretched into the Shyok Suture Zone and Asian plate by this time, and was therefore  
298 likely the palaeo-Indus. However, we suggest that such grains may also be derived from the Indian  
299 Himalayan units south of the KLIA, as arguable by their occurrence in the Siwalik foreland basin

300 sedimentary rocks of Nepal, that were deposited by rivers which did not stretch back to Asia (Bernet et  
301 al., 2006).

302 However, more definitive evidence of deposition from the palaeo-Indus comes from detrital mica Ar-Ar  
303 data. Lag times of detrital mica Ar-Ar ages from Kamlial Formation Potwar Plateau sedimentary rocks  
304 indicate rapid exhumation of the upland source region from 16-14 Ma (Najman et al., 2003). The  
305 exhuming source area was interpreted by those authors to be the Karakoram and/or Nanga Parbat  
306 region, consistent with both bedrock data from those regions (Treloar et al., 2000; Zhuang et al., 2018  
307 and references therein). Due to their locations, derivation of micas from either location strongly  
308 suggests transport by a palaeo-Indus. Furthermore, detritus delivered by possible ancient smaller  
309 tributaries draining only the Indian plate and arc would have had a distinct and different signature, with  
310 a higher proportion of Indian plate detritus, for example the Mid Miocene Kamlial Formation sample  
311 CP96-6A from Najman et al. (2003), and presumably those samples from the Eocene Kuldana Formation  
312 with a high proportion of old zircons at Muzaffarabad (Ding et al., 2016b) (see section 5.2 for further  
313 discussion).

#### 314 *2.3.4. Evolution of the Lower Indus palaeodrainage*

315 Within the basin, the position of the Ganges-Indus drainage divide over time is long debated, with  
316 various authors proposing that parts of the current Gangetic catchment used to flow into the Indus Fan  
317 (e.g. DeCelles et al., 1998), and the current Indus River catchment into the Bengal Fan (e.g. Burbank et  
318 al., 1996) at various times. Clift and Blusztajn (2005) noted a change to more negative  $\epsilon_{Nd}$  values in the  
319 Indus Fan at 5 Ma, which they interpreted as the drainage diversion of the major Indian-plate draining  
320 Punjabi Indus River tributary system of the Jhelum, Chenab, Ravi and Sutlej rivers (Figs. 1A and C) from a  
321 previous routing towards the Ganges and the Bengal Fan to the east.

322 However, the above argument was countered by Chirouze et al. (2015) who looked at both spatial and  
323 temporal trends at the range front and Indus Fan. They considered that the change in the signal was due  
324 to differential exhumation in the hinterland rather than drainage re-organization. They compared  $\epsilon_{Nd}$   
325 data between the range front and Indus Fan for both the present day and the Miocene (using Chinji  
326 Formation foreland basin data for the Miocene range front). They recorded a spatial variation of four  $\epsilon_{Nd}$   
327 units between the range front and the Indus Fan for both mid-late Miocene times and modern day  
328 (Miocene range front and Indus Fan values at -6 and -10 respectively; modern day range front and Indus  
329 Fan values at -10 and -14 respectively. This suggests a stable drainage pattern for the lower Indus since  
330 at least the mid-late Miocene. From the above data they noted a negative shift of  $\sim 3$   $\epsilon_{Nd}$  units between  
331 Miocene and the modern day at both the range front (comparison of Miocene foreland basin  
332 sedimentary rocks with modern day Upper Indus values) and a similar shift in the Indus Fan. From this  
333 temporal shift they therefore concluded that the variation over time was due to the changing  
334 exhumation rates of the contributing source regions, with the exhumation and thus contribution of the  
335 Karakoram / Indian plate syntaxial Himalaya increasing at the expense of the more positive KLIA (Table  
336 1) to explain the shift in  $\epsilon_{Nd}$  values in the Indus Fan at 5 Ma. They supported their proposal of variations  
337 in exhumation using detrital zircon fission track (ZFT) data, interpreting a decrease in older ZFT ages  
338 after 12 Ma as due to decreased input from the KLIA. Later, the original proponents of the drainage  
339 capture hypothesis (Clift and Blusztajn, 2005) concurred with the view of Chirouze et al. (2015) that  
340 changes in the tectonics of the hinterland was the more likely cause of the geochemical change in the  
341 Indus Fan at 6 Ma (Clift et al., 2019; Zhou et al., 2022) thus the time when the Punjab tributary system  
342 joined the trunk Indus remains unknown. It is towards this question, namely the evolution of the  
343 downstream Indus, that this paper focusses.

344 The location of the exit of the Indus River to the ocean in the past retains a level of uncertainty. Today  
345 the Indus River debouches to the Arabian sea at the south of the Lower Indus axial Basin. These deposits



346 are recorded in eastern Sulaiman and Kirthar regions of the Lower Indus Axial Basin (Welcomme et al.,  
347 2001) (Fig 1A). Zhuang et al. (2015) show that zircons from the KLIA are recorded in these sediments  
348 from at least early Oligocene times; they considered that detrital zircon U-Pb data indicate input from  
349 the Karakoram from at least Mid Miocene times, and that Sr-Nd data indicate a palaeo-Indus origin from  
350 50 Ma. Roddaz et al. (2011) carried out mixture modelling on their Sr-Nd data and concluded that there  
351 was an appreciable input from the Karakoram since 50 Ma.

352 However, Palaeogene deltaic facies have also been identified in the Katawaz remnant ocean Basin (Fig  
353 1A) to the west (Qayyum et al., 2001). In view of the differing compositions and provenance between  
354 these two deltaic systems, Roddaz et al. (2011) proposed two river-delta-fan systems, with the Katawaz  
355 system debouching into the Khojak submarine fan and the sediments of the Lower Indus Axial Basin  
356 debouching into the Indus Fan. Provenance data from the Katawaz rocks show that that drainage basin  
357 stretched back at least as far as the KLIA by Miocene times (Carter et al, 2010) with a paucity of data  
358 currently precluding earlier documentation. For a full evaluation of the Indus river-delta-fan system and  
359 the spatial evolution, more data are needed from the Katawaz basin; data presented in this paper  
360 provide a direct comparison between peripheral foreland basin records and terminal sinks in the delta  
361 and ocean.

362

### 363 **3. Methods**

#### 364 ***3.1 Rationale and approach***

365 To determine when the Punjab tributary system joined the trunk Indus, we leverage that fact that the  
366 tributaries have a very different drainage basin lithology to the trunk Indus; the former includes only  
367 Himalayan units, whilst the drainage basin of the latter includes also the KLIA and Asian plate (Fig. 1C),  
368 which have very different isotopic and geochemical signatures to the Indian plate (Table 1). This

369 difference is clearly reflected in both the Sm-Nd and zircon U-Pb characteristics of the trunk Indus river  
370 versus the Punjabi tributary system: Figs 2 and 3A (inset) shows that, compared to the modern Indus  
371 trunk river, the Punjabi tributaries have a more negative  $\epsilon_{Nd}$  value and a much lower proportion of  
372 young arc-aged grains (Alizai et al. 2011, Chirouze et al 2015), a signature which extended back into the  
373 ancient sedimentary record (Exnicios et al., 2022; Najman et al., 2009).

374 We took a similar approach to Chirouze et al (2015) in hypothesising that prior to the time when the  
375 Punjab tributary system joined the trunk Indus River, the sedimentary repositories upstream and  
376 downstream of the confluence should look similar in terms of provenance. After the time when the  
377 tributary system joined the Indus River, the repository upstream of the confluence should remain similar  
378 (unless synchronously affected by a tectonic-induced change in the hinterland), but the downstream  
379 repository should show increased input from Himalayan Indian plate units.

380 We therefore made comparison between data upstream (our new foreland basin data) and published  
381 data downstream of the Punjab tributary system. Previous work used the Indus Fan as the downstream  
382 comparative repository. We use both the deltaic record in the Sulaiman and Kirthar region, and the  
383 Indus Fan archive, since onshore sedimentary archives are typically more prone to diagenetic alteration  
384 compared to marine records, whilst distal deposits are more prone to the effects of hydraulic sorting  
385 (e.g., Garzanti et al., 2020) and contain evidence of subordinate extraneous (non-Indus River) sources to  
386 the Himalayan orogen, such as the Deccan Traps of peninsular India input to the Indus Fan (Clift et al.,  
387 2019; Garzanti et al., 2020; Yu et al., 2019). The Indus Fan record is a composite repository of material  
388 recovered from the Owen Ridge and Western Fan from DSDP 224 (Eocene-Miocene) and ODP 720, 722  
389 and 731 (Eocene-Pleistocene) sites, and IODP 355 sites of U1456 and 1457 of the Eastern Fan (Neogene  
390 only) (Clift et al., 2019; Feng et al., 2021; Zhou et al., 2022) (Fig. 1A).

391 Our dataset builds on the previous work of Chirouze et al. (2015) in two ways. Firstly, it expands the  
392 time range from the previous mid Miocene study of the Pakistan peripheral foreland basin to now  
393 include foreland basin rocks from Eocene to late Miocene. This allows a more complete assessment of  
394 the evolution of the lower Indus to be determined. Secondly, we incorporate not only  $\epsilon_{Nd}$  data from  
395 mudstones, but also new and previously published zircon U-Pb data to assess provenance, and mica  
396  $^{40}Ar/^{39}Ar$  data to assess exhumation. Therefore, in addition to using both onshore and offshore  
397 repositories to limit the potential effects of fertility, diagenetic, and hydraulic sorting biases, our multi-  
398 proxy approach provides additional mitigation since: 1) zircons are resistant to diagenesis; 2) we assess  
399 evidence from both the mud and sand grain size fractions with the use of both bulk and single grain  
400 approaches and 3) we obtain data from both zircon and mica grains which respond differently to the  
401 hydraulic regime (e.g., Garzanti and Andò, 2019; Garzanti et al., 2009; Malusà et al., 2016). Furthermore,  
402 since white mica is rare in the KLIA, exhumation patterns of the Karakoram and Indian plate Himalaya  
403 can be considered in isolation using this technique, unbiased by potential issues surrounding dilution  
404 and fertility.

405

## 406 **3.2. Samples and analyses**

### 407 *3.2.1 Samples*

408 We analysed 5 sandstones for detrital zircon, 10 mudstones for Sr-Nd isotopes, and 3 sandstones for  
409 mica  $^{40}Ar/^{39}Ar$ . The locations of analysed samples (Figs. 1A and B) are from the Kuldana Formation in the  
410 HKS at Paras north of Balakot, the Murree Formation in both the HKS and at Murree Hill Station (MHS),  
411 and the Kamlial, Chinji and Nagri Formations from the Chinji section on the Potwar Plateau, the latter  
412 being the same location from which Chirouze et al (2015) took their samples. A summary of our sample  
413 information is tabulated in S1. Our samples from the Kuldana Formation are structurally imbricated  
414 within the Murree Formation (Najman et al., 2002). Originally, Najman et al (2002) considered these

415 structural imbrications to be Patala Formation, based on the work of Bossart and Ottiger (1989) who did  
416 not recognise the Kuldana Formation. However, more recent detailed mapping (Ding et al., 2016b) and  
417 the better agreement of biostratigraphic ages from the structural imbricates (early-mid Eocene; Bossart  
418 and Ottiger (1989)) with the Kuldana Formation rather than Patala Formation (section 2.2.1), suggests  
419 reassignment of these imbricates from the Patala to the Kuldana Formation.

### 420 *3.2.2 Sr-Nd bulk analyses*

421 Sr and Nd isotope analyses on bulk mudstones were carried out at the NERC Isotope Geosciences  
422 Laboratory, Keyworth, Nottingham. Samples were leached in dilute acetic acid in order to remove  
423 carbonate material, then dissolved using HF-HNO<sub>3</sub> and converted to chloride form. Sr and a bulk REE  
424 fraction were separated using AG50x8 cation columns, and Nd was separated from the bulk REE using  
425 LN-SPEC columns. Sr and Nd were analysed on a Thermo Scientific Triton mass spectrometer.

### 426 *3.2.3 Zircon U-Pb analyses*

427 Detrital zircon U-Pb ages were acquired using laser ablation ICPMS, at the London Geochronology  
428 Centre, University College London. To avoid bias, polished grain mounts were made, without hand  
429 picking, directly from Diidomethane sink fractions with a grain size  $\leq 300 \mu\text{m}$ . Each laser spot (25  $\mu\text{m}$ )  
430 was placed on the outermost parts of each grain to target the youngest growth stage. Between 150-320  
431 grains were analysed for each sample, providing statistical confidence of detecting all component ages.  
432 Data were processed using GLITTER v4.4 data reduction software using age standard bracketing to  
433 correct for mass fractionation. Between 8 and 15% of ages were rejected, due to high discordance from  
434 lead loss, zoning or mixing of growth zones. One exception was the Chinji Formation that contained an  
435 unusually high number (60%) of discordant grains. Most of these discordant grains are associated with  
436 ages between 75-120 Ma and consistent with lead loss, likely due to source weathering.

#### 437 3.2.4 Muscovite Ar-Ar analyses

438 Muscovite Ar-Ar ages were analysed at the Argon Geochronology Laboratory at VU University  
439 Amsterdam, Netherlands. Individual grains ranging from 125-1000  $\mu\text{m}$  were handpicked under a  
440 binocular microscope to avoid obvious weathering or inclusions. After irradiation at the Oregon State  
441 University TRIGA nuclear reactor, total fusion analyses were carried out with a ThermoFisher Scientific  
442 Helix MC plus multi-collector mass spectrometer, fitted with  $10^{13}$  Ohm amplifiers. Data reduction was  
443 done using ArArCALC2.5 (Koppers, 2002).

444 Detailed methodologies are provided in SI 1, and results are reported in Tables S1 (Sr-Nd data), S2  
445 (zircon U-Pb data) and S3 (mica Ar-Ar data).

446

### 447 **4. Results and integration with published data**

#### 448 **4.1 Sr/Nd bulk (Figs. 2 and SI Fig S1, Table S1)**

449 There is little significant variation in  $\epsilon_{\text{Nd}}$  values from the Eocene Kuldana Formation through to the late  
450 Miocene Nagri Formation, with values ranging between -7.0 to -9.2 (Fig. 2A). The exception to this  
451 overall similarity is the Murree Formation at MHS, with a value of -13.8. We note that previous work for  
452 the Chinji Formation records values of -3.8 to -7.7 (Chirouze et al., 2015); this difference could perhaps  
453 reflect the previous use of sand compared to analysis of muds in the current research (see Jonell et al.,  
454 2018 for further discussion). There are no modern-day data available for the range front. The Upper  
455 Indus has a value of -10.8 at Besham (Clift et al., 2002b) located just downstream of the Kohistan arc  
456 (Fig. 1B and C) and we can extrapolate that values should be more negative than this at the range front,  
457 after the river has passed over the Greater and Lesser Himalaya. Values at the delta front at Thatta are -  
458 14.9 (Clift et al., 2002b).

459 We carried out mixture modelling on the foreland basin material (SI Fig. S1). The mixture modelling is  
460 complicated by the number of end member contributors; today sediment in the Upper Indus River  
461 contains material from the Lhasa Block, Karakoram, KLIA, suture zone, and the Indian plate units of the  
462 Greater-, Lesser- and Tethyan Himalayan correlatives. Overlapping signatures of some units (e.g.  
463 between the Karakoram and Tethyan Himalaya, and between the KLIA and ophiolitic melange of the  
464 suture zone) also adds uncertainty. We started with the premise that, from the zircon data we are  
465 confident that the foreland basin contains material from the KLIA (section 4.2.) from the oldest  
466 sediments studied, namely the early-Mid Eocene Kuldana Formation. That therefore forms the apex of  
467 our model, and various mixture couplings are calculated with this apex and other potential end  
468 members. The modelling shows that all data can be explained by a mix of Indian plate and KLIA inputs,  
469 and contribution from the Karakoram and Lhasa Block is equivocal. The Murree Formation sample from  
470 MHS requires considerable input from Greater Himalayan lithological correlatives.

471 The Sr-Nd compositions of the samples plot on trends that are consistent with simple mixing between  
472 mafic and more evolved sources. There is some scatter in the data towards high  $Sr^{87}/Sr^{86}$  values that  
473 may result from weathering or diagenesis. However, we are confident that the dominant trends reflect  
474 changes in provenance, as described above.

#### 475 ***4. 2 Detrital zircon U-Pb analyses (Fig 3, SI Figs S2 and S3, Table S2)***

476 We compile our new data from the Murree Formation at Paras north of Balakot in the HKS and at MHS  
477 (< 24 Ma), and from the Kamliyal (18-14 Ma), Chinji (14-11 Ma) and Nagri (11-8.5 Ma) Formations in the  
478 Potwar Plateau, with previously published data from the Kuldana and Murree Formation rocks at  
479 Balakot, Muzaffarabad and Kotli in the HKS and at MHS (Awais et al., 2021; Ding et al., 2016a; Qasim et  
480 al., 2018) and modern river data collected at the MCT-correlative (Khairabad Thrust) at the range front  
481 at Attock (Alizai et al 2011, Clift et al 2022) (Fig. 1B). We keep our observations of comparisons broad

482 and conservative in nature, since different approaches to both mineral separation and data processing  
483 procedures by different labs can cause variation in proportions of different populations. We begin our  
484 summary at the marine to continental transition (the Kuldana Formation, section 2.2.1). We focus on  
485 the 40-200 Ma “arc-aged” population characteristic of the KLIA and Karakoram, and the older grains  
486 typical of the Indian plate and Karakoram, with emphasis on the 1500-2300 Ma population typical of the  
487 Lesser Himalayan lithological correlatives and 300-1250 Ma population typical of the Greater Himalayan  
488 lithological correlatives (section 2.1.1, Table 1).

489 With the exception of the Murree Formation (which we portray separately in Fig 3B and discuss  
490 separately in section 5.2), the proportions of the 40-200 Ma “arc-aged” populations remain approaching  
491 or above 50% throughout the Neogene to present day. There is much variation within the Eocene  
492 Kuldana Formation, with nevertheless a number of samples also showing a majority of grains to be arc  
493 aged (Fig. 3A, Table 1). By contrast, the Murree Formation has a very low proportion of grains in the 40-  
494 200 Ma range in all samples analysed from MHS, Muzaffarabad and Balakot, although not at Paras north  
495 of Balakot in the HKS (Fig 1B, Fig 3B and SI Fig S2). Instead, these Murree Formation samples from MHS,  
496 Muazaffarabad and Balakot have a high proportion of grains with ages typical of the Greater Himalaya.  
497 In contrast to the modern-day river sample at Attock (Fig. 3C, Fig 1B), there is no 1500-2300 Ma  
498 population typical of the Lesser Himalayan lithological correlatives, in any of the formations.

#### 499 **4.3 Mica Ar-Ar (Fig 4, SI Fig. S4, Table S3)**

500 We have integrated our new data from the Murree Formation at MHS, Chinji and Nagri Formations with  
501 previous data from the Murree Formation in the HKS at Paras north of Balakot (Najman et al., 2001) and  
502 Kamlial Formation (Najman et al., 2003) (SI Fig. SI4). We note the following, bearing in mind that the  
503 number of grains analysed for the Murree Formation at Paras north of Balakot (n=257) and the Kamlial  
504 Formation (n=277) are considerably higher than for the Murree Formation at MHS, Chinji and Nagri

505 samples (n=59, 94 and 43 respectively), resulting in more confidence that the Balakot and Kamliial  
506 Formation datasets more completely capture the complete spectrum of ages:

507 The youngest grain in the Murree Formation at Paras in the HKS is 24.6 +/- 0.7 Ma, the weighted mean  
508 of the youngest two grains overlapping within error at two sigmas is 24.8 Ma +/- 1.4 Ma and the  
509 youngest peak population is 37 Ma. Pre-Cenozoic ages extend to >1500 Ma. Further south, the youngest  
510 grain in the Murree Formation at MHS is 23.7 +/- 0.1 Ma, which also forms one of the two youngest  
511 grains overlapping within error at 2 sigmas (weighted mean 23.85 +/- 0.12 Ma. The youngest peak  
512 population is 24-28 Ma. Pre-Cenozoic ages extend to ca 450 Ma. The youngest grain for the Kamliial  
513 Formation is 14.5 +/- 0.7 Ma, and weighted mean of the youngest two grains within error at 2 sigmas is  
514 15.00 +/- 1.10a. The youngest peak population is 18 Ma and Pre-Cenozoic ages extend to ca 450 Ma. The  
515 lowest Chinji Formation sample (CP96-7A, Najman et al 2003, dated at 13.9 Ma) has a youngest grain at  
516 14.1 +/- 0.7 Ma and this also forms one of the two youngest grains within error at 2 sigmas (weighted  
517 mean 14.43 +/- 0.81 Ma). Pre-Cenozoic grains extend to 400 Ma. Our new sample from the Chinji  
518 Formation has a youngest grain of 16.74 +/- 0.1 Ma, the weighted mean of the two youngest grains  
519 overlapping within error at 2 sigmas is 25.95 +/- 0.10 Ma, the youngest peak population is 28-29 Ma,  
520 and Pre-Cenozoic ages extend to ca 450 Ma. The youngest grain in the Nagri Formation is 17.9 +/- 0.14  
521 Ma, the weighted mean of the two youngest two grains overlapping within error at 2 sigmas is 19.69 +/-  
522 0.12 Ma the youngest peak population is 21 Ma and Pre-Cenozoic ages extend to ca 200 Ma.

523 Rapid exhumation determined from short lag times was determined for the Kamliial and lowest Chinji  
524 Formation, between 16-14 Ma (Najman et al, 2003) (Fig. 4). Lack of independent depositional age  
525 constraints precludes calculation of lag times for the newly analysed Murree, Chinji and Nagri Formation  
526 samples. Up section from the Kamliial Formation, there is no evidence of grain ages approaching



527 depositional age, until the modern river sample at Thatta, although the number of grains analysed is  
528 relatively small.

529

## 530 **5. Interpretations of the evolution of the Lower Indus drainage**

### 531 ***5.1. When did the Punjabi tributary system join the paleo-Indus trunk river?***

532 As outlined in our rationale and approach (section 3.1), we determine when the Punjab tributary system  
533 joined the main trunk river, by a comparison of provenance data from upstream and downstream of the  
534 present day confluence, leveraging the fact that unlike the palaeo-Indus trunk River, the tributaries  
535 drain only the Indian plate terranes (Fig 1C), and thus have a different provenance signature (section  
536 3.1, Figs 2 and 3A inset).

537 As schematically presented in Fig 5, the following evidence should be met, at the time the tributary  
538 system joined the trunk Indus:

539 (1) Prior to the time that the Punjab tributary system joined the Indus catchment, the proportion  
540 of Indian plate detritus delivered to the Indus River should be comparable at the range front and  
541 at the river mouth, i.e. upstream and downstream of where the Punjab tributary system now  
542 joins the modern Indus.

543 (2) After the time when the Punjab tributary system joined the Indus River, the proportion of Indian  
544 plate material in the Indus River downstream of the confluence with the Punjab Rivers should a)  
545 increase relative to the downstream's previous pre-reorganisation proportion and b) be greater  
546 than coeval sediments upstream. However, the proportion of Indian plate material in the  
547 upstream should remain constant, pre and post the proposed drainage reorganisation.

548 For the above predictions to be explored, Indian plate, versus Karakoram, versus KLIA must be  
549 differentiable in the foreland basin detritus. Table 1 provides the typical zircon U-Pb and  $\epsilon_{Nd}$  signatures  
550 of these units, alongside a summary of equivalent data from the peripheral foreland basin, and  
551 downstream in both the Sulaiman-Kirthar region and Indus Fan. Figs 2 and 3A inset show the difference  
552 between the modern trunk Indus which drains the Asian plate, arc and Indian plate, versus the modern  
553 Punjabi tributary system which drains, for the most part, only the Indian plate.

554 For the interpretations made from this upstream-downstream comparison to be valid, the rocks at the  
555 evaluated locations must be the products of the palaeo-Indus. Whilst all three repositories studied, the  
556 peripheral foreland basin, the Lower Indus Axial Basin, and the Indus Fan, show evidence of derivation  
557 from at least as far north as the KLIA since Eocene times, we acknowledge evidence for input from north  
558 of the Shyok suture zone can be equivocal (see sections 2.3.1, 2.3.3 and 2.3.4).

559 Below, we summarise the salient points regarding the upstream and downstream repositories that are  
560 relevant to the characteristics required to document the timing of conjoinment of the Punjabi tributary  
561 system with the trunk Indus River as described above. We discuss the Murree Formation which is  
562 anomalous at MHS, Muzzafarabad and Balakot, but not at Paras, separately in section 5.2.

563 *5.1.1. Comparison of the upstream peripheral foreland basin material with the downstream repositories*  
564 *in terms of Sr-Nd data*

565 Our data from the upstream (peripheral foreland basin) show that values have remained broadly  
566 constant from the start of our studied record in the early-Mid Eocene Kuldana Formation (Fig. 2A), until  
567 the late Miocene Nagri Formation, when values become a little more negative.  $\epsilon_{Nd}(0)$  values in the  
568 downstream repositories are similar to the upstream in the early Eocene. However, values in the  
569 downstream repositories become more negative compared to the upstream, by Mid Eocene in the Indus

570 Fan and around the Eocene-Oligocene boundary in the Lower Indus Axial Basin (Fig. 2B). This shift  
571 indicates a greater input of material from the Indian plate Himalayan terrane at this time.

572 From the more negative  $\epsilon\text{Nd}(0)$  values recorded below compared to above the confluence throughout  
573 the Neogene, we interpret that the Punjabi tributary system has drained into the palaeo-Indus  
574 throughout the Neogene, and that the present drainage configuration was therefore established during  
575 the Paleogene.

576 The consistency of  $\epsilon\text{Nd}$  values from the Eocene to the Neogene in the upstream repository, in contrast  
577 to the shift to more negative values in the downstream repositories should reflect the time when the  
578 Punjabi tributary system joined the trunk Indus River. However, the difference in the time of the  
579 downstream shift, at the Eocene-Oligocene time in the Lower Indus axial basin delta deposits and in the  
580 mid Eocene in the Indus Fan indicates that more research is required before we can pinpoint the exact  
581 time that the tributary system joined the trunk Indus. Nevertheless, with available data we can conclude  
582 that the tributaries joined in the trunk Indus at or before the start of the Oligocene (Fig 5).

583 *5.1.2. Comparison of the upstream peripheral foreland basin material with the downstream repositories*  
584 *in terms of detrital zircon U-Pb data*

585 Although intraformational variability, lack of data from the Oligocene in the peripheral foreland basin,  
586 and lack of data from the Eocene in the downstream repositories limits the comparison, the data are  
587 consistent with the interpretations determined the Sm-Nd data, that the Punjabi tributary system joined  
588 the trunk River Indus by Oligocene times (section 5.1.1, Fig 5): The proportion of 40-200 Ma arc-aged  
589 grains remains high throughout the Miocene in the peripheral foreland basin, and these values are  
590 higher compared to Oligocene-Pliocene values in both downstream repositories (Fig. 3A and C, Table 1).  
591 Data from the Eocene peripheral foreland basin is highly variable. However, at least some samples have

592 a proportion of arc-aged grains similar to the proportions of the Neogene peripheral foreland basin,  
593 consistent with the pattern shown in the Sm-Nd data.

594 SI Figure SI 3 illustrates the river's evolution well, particularly by comparison to the Lower Indus Axial  
595 Basin. Downstream samples have a greater affinity to Indian plate rocks and the modern Indus at its  
596 mouth at Thatta, compared to the upstream peripheral foreland basin rocks which have greater affinity  
597 to the arc and Asian plate, and the modern day Indus at the range front at Attock.

598 The variation in zircon U-Pb age spectra, and also in  $\epsilon_{\text{Nd}}$  values, between the onshore and offshore  
599 downstream palaeo-Indus, and between the Eastern and Western Indus Fan (SI Figs. S1 and S3) is  
600 intriguing. It could be the result of a number of factors, for example differences in sample preparation  
601 procedures between operators, downstream influence of hydraulics, or additional material contributing  
602 downstream, for example.

## 603 **5.2. Interpretation of the Murree Formation**

604 Compared to the other peripheral foreland basin sediments sampled, the Zircon U-Pb data show  
605 significantly higher proportions of old grains in the Murree Formation at MHS, Kotli, and at Balakot and  
606 Muzaffarabad in the HKS, but not at Paras north of Balakot (Fig. 3B, SI Fig S2, Table 1). Where  
607 accompanying Sr-Nd data are available (MHS and Paras only), there is a corresponding change to more  
608 negative  $\epsilon_{\text{Nd}}$  values at MHS (Fig 2A), mirroring the change noted in the zircon data. This signature  
609 indicates a higher proportion of material derived from the Indian plate (see also SI Fig S3). These  
610 deposits may be interpreted as the palaeo-Jhelum Punjab tributary, which has a similar zircon U-Pb  
611 spectrum to the Murree Formation (Fig. 3B), and a drainage basin consisting predominantly of the  
612 Indian plate (Fig 1C). The spatial distribution of our analysed samples is consistent with this  
613 interpretation: a Himalayan-derived palaeo-Jhelum type signature is prevalent in Murree Formation  
614 samples at Muzaffarabad (Fig 1B) located on the modern day Jhelum River, at MHS downstream and ca

615 10 miles to the west of the modern Jhelum River, and at Kotli, downstream and 20 kms east of the  
616 modern Jhelum river. It is also prevalent at Balakot, ca 15 miles upstream of the modern Jhelum River,  
617 which we suggest could have been in the flood plain of the palaeo-Jhelum. 5 miles further north still,  
618 near Paras, the signature is more arc-like and in this palaeo-drainage scenario, we propose lies outwith  
619 the floodplain of the palaeo-Jhelum. We note that at Muzaffarabad only, through which the modern  
620 Jhelum River flows, a palaeo-Jhelum type signature is also recorded, in some samples, in the underlying  
621 Eocene Kuldana Formation. This may reflect the early initiation of this river, insufficiently large in its  
622 early evolution to affect the downstream.

623 Alternatively, the anomalous signature from the Murree Formation compared to the rest of the  
624 Cenozoic sediments in the peripheral foreland basin may reflect increased input from the Himalaya  
625 attributable to a pulse of exhumation recorded in the Himalaya in the early Miocene (section 2.1.2). A  
626 coeval change to greater input from the Indian plate is also recorded in the Indus Fan (Feng et al., 2021)  
627 and Kirthar Ranges (Zhuang et al., 2015), supporting this interpretation. Further analyses from Murree  
628 Formation samples distal to the Jhelum River should distinguish between these two alternative  
629 hypotheses.

630 The difference in Murree signature compared to the rest of the foreland basin cannot be ascribed to  
631 bias associated with grain size variation since the difference is reflected in both bulk rock Sr-Nd and  
632 zircon proxies. Nor is there any reason to consider that a potential difference in the degree of diagenesis  
633 caused the difference, since zircons are largely unaffected by this process.

### 634 ***5.3 What caused the change in the geochemical signature of the Indus Fan at 5-6 Ma?***

635 The more recently proposed alternatives to drainage reorganisation (Clift and Blusztajn, 2005) to  
636 explain the geochemical shift in the Indus Fan at 5-6 Ma all involve tectonic explanations, namely  
637 variations in exhumation of the hinterland terranes, although the extent to which increased exhumation

638 of the Lesser Himalaya versus Greater Himalaya versus Karakoram is responsible, is debated (Chirouze et  
639 al 2015, Clift et al 2019, Zhou et al. 2022). Changes in monsoonal intensification are not thought to have  
640 been a major influence (Clift et al., 2019, Zhou et al 2022).

641 To what extent do our data support a tectonic explanation? We focus on the peripheral foreland, which  
642 should provide the most tectonically- influenced archive, above any downstream influence from the  
643 Punjabi tributary system. We compare our data from the Nagri Formation (11-8.5 Ma; Table 1) to  
644 modern day Indus data at the range front, this time period encompassing the 5-6 Ma date over which  
645 the geochemical shift in the Indus Fan occurred.

646 The average  $\epsilon\text{Nd}$  value of the two samples from the Nagri Formation is -9.65. No data are available for  
647 the modern Indus at the range front. The spatially closest sample is from Besham, just south of the MCT  
648 (Fig. 1C). This sample has a value of -10.7, and we would expect a more negative value by the time the  
649 river had crossed to the range front, having flowed over more of the Greater Himalaya and most  
650 negative Lesser Himalaya (Table 1). Thus, the shift to more negative  $\epsilon\text{Nd}$  values between the Nagri  
651 Formation and the estimated value for the range front in modern times I shows that variation in upland  
652 tectonics over this time period could have resulted in the shift to more negative  $\epsilon\text{Nd}$  values seen in the  
653 Indus Fan over this time period.

654 Assignment of zircon U-Pb age populations to distinct provenances is challenging with respect to overlap  
655 of the older Karakoram and Indian plate grains. Nevertheless, the 1500-2300 Ma population is typical of  
656 the Lesser Himalaya. This population makes up 3% of the Nagri sample. There is no sample from the  
657 modern Indus River at the range front. However, there is a sample from upstream at Attock (Fig. 1C).  
658 This sample has an 11% contribution from the 1500-2300 Ma population, and we would predict a higher  
659 proportion of that population after the river has flowed over a greater proportion of Indian plate  
660 material. The shift to a higher proportion of zircons with ages indicative of Lesser Himalayan input

661 between the Nagri Formation and the modern day (Fig 3), therefore supports our observations from the  
662 Sm-Nd data, that upstream variations in tectonics could have resulted in the geochemical shift in the  
663 Indus Fan.

664 There are no modern river mica  $^{40}\text{Ar}/^{39}\text{Ar}$  data from the range front. Modern river  $^{40}\text{Ar}/^{39}\text{Ar}$  mica data  
665 from the trunk Indus at its river mouth at Thatta shows Plio-Pleistocene grains (1-5 Ma) indicative of  
666 rapid exhumation (Clift et al., 2004). Recording of these young grains in the trunk river but not in the  
667 tributaries draining only the Indian plate or Indian plate plus Hindu Kush (Clift et al., 2004; Najman et al.,  
668 2009; Zhuang et al., 2018) is consistent with the viewpoints of, for example, Chirouze et al. (2015) and  
669 Clift et al. (2022) Clift et al (2022), that the Karakoram and/or the Nanga Parbat syntaxis supplied this  
670 young material. Lag times determined from mica data from the Neogene peripheral foreland basin  
671 sedimentary rocks show no clear indication of rapid exhumation of the micas' source region after 14-16  
672 Ma (Fig. 4) although n values are small and therefore populations may have been missed. Therefore a  
673 period of rapid exhumation occurred sometime between Nagri Formation times and present day,  
674 consistent with the view that changing exhumation in the hinterland was responsible for the  
675 geochemical shift at 5 Ma in the Indus Fan.

676

## 677 **6. Conclusions**

678 When the lower Indus River broadly attained its current drainage configuration, in particular when the  
679 Punjab tributary system joined the main trunk river, is undocumented. Comparison of  $\epsilon_{\text{Nd}}$  bulk rock data  
680 and detrital zircon U-Pb data from Cenozoic paleo-Indus sedimentary rocks both upstream and  
681 downstream of the confluence of the Indus with the Punjab tributary system shows that throughout the  
682 Neogene, greater proportions of Indian plate material are recorded in the downstream compared to the

683 upstream repositories. We therefore conclude that the Punjabi tributary system, which transports  
684 predominantly Indian plate detritus, had joined the trunk Indus River prior to the Neogene.

685 Whilst provenance indicators show that the proportion of Indian plate material remains constant from  
686 Eocene to Neogene in the palaeo-Indus repository upstream of the confluence, the proportion of Indian  
687 plate material increases in the downstream repositories, at the Eocene-Oligocene boundary in the  
688 palaeo-delta, and in the mid Eocene in the Indus Fan. More research is required to understand the  
689 reasons for this discrepancy in timing of the shift in the downstream repositories, but nevertheless we  
690 can conclude that the Punjabi tributary system joined the palaeo-Indus trunk river at or before the start  
691 of the Oligocene.

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## 698 **Figures**

699 **Figure 1: A:** Map showing modern drainage of the Indus River with the Punjab tributary system, and the  
700 Indus Fan (black dotted line). Also shown are the onshore lower Indus (Kirthar and Sulaiman) and  
701 offshore IODP, ODP and DSDP locations of previously published data (Roddaz et al. 2011, Zhuang et al  
702 2015, Clift et al. (2001), Clift and Blusztajn (2005), Clift et al. (2019) and Feng et al (2021). with which we  
703 compare our new upstream data. Black rectangle shows the location of Fig 1B. **B:** locations of new data  
704 (this study) and various towns and published sample sites discussed in text. MHS = Murree Hill Station;



705 HKS = Hazara-Kashmir Syntaxis. Samples with prefix KG96 or 99 are from Paras in the HKS, prefix MU96  
706 are from Murree Hill Station, and prefix KMSr, CHSr, and NgSr are from Chinji village area. **C:** Drainage  
707 superimposed on regional geology (from Clift et al., 2019). ISZ = Indus Suture zone, SSZ = Shyok Suture  
708 Zone, MCT =Main Central Thrust, MBT=Main Boundary Thrust, MFT = Main Frontal Thrust.

709 **Figure 2:**  $\epsilon_{Nd}$  values from the upstream peripheral foreland basin in Pakistan (A), and downstream Lower  
710 Indus axial basin and Indus Fan (B) through time. In A, numbers adjacent to squares refer to sample  
711 numbers to left. Asterisks indicate new data. Open squares for modern Indus River at Besham and  
712 Thatta; hexagons are from the modern Punjabi tributaries (data from Clift et al 2002, Alizai et al. 2011,  
713 Chirouze et al 2015). In B: diamonds – data from the Sulaiman and Kirthar regions of the Lower Indus  
714 axial basin (Roddaz et al, 2011, Zhuang et al 2015); circles – data from the Indus Fan from Clift et al.  
715 (2001), Clift and Blusztajn (2005), Clift et al. (2019), Zhou et al 2021, and Feng et al (2021). Questions  
716 marks next to three Mid Eocene samples represent uncertainties in age for those samples, as depicted in  
717 the original publication of Clift et al (2001). HKS = Hazara-Kashmir Syntaxis; MHS = Murree Hill Station.  
718 MDA = maximum depositional age as determined from detrital grain ages (sections 2.2.1, 4.2 and 4.3).  
719 Grey horizontal shading between plots A and B denote roughly equivalent time periods.

720 **Figure 3:** Detrital zircon U-Pb data shown as cumulative age distribution plots. **A:** Pakistan peripheral  
721 foreland basin data excluding Murree Formation data except our new data. Kuldana Fm samples are  
722 Early-Mid Eocene, Murree Formation samples are Early Miocene, Kamliyal Fm is Early-Mid Miocene,  
723 Chinji Fm is Mid Miocene, Nagri Fm is Late Miocene (Table 1). A inset: modern river data comparing the  
724 Indus at the range front at Attock, with rivers of the Punjabi tributary system. **B:** all Murree Formation  
725 data, both new and published, with comparison to the Jhelum modern river data. Murree Formation is  
726 Early Miocene. **C:** comparison between peripheral foreland basin data and downstream Lower Indus  
727 axial basin data and (inset) Indus Fan data. Eocene peripheral foreland basin data are omitted from the

728 figure as there are no comparative data from the downstream repositories. HKS = Hazara-Kashmir  
729 Syntaxis, MHS = Murree Hill Station. All new data are asterisked. Samples with superscripts are  
730 published data, as follows: <sup>1</sup>Ding et al (2016), <sup>2</sup>Qasim et al (2018), <sup>3</sup>Awais et al (2021), <sup>4</sup>Zhuang et al  
731 (2015), <sup>5</sup>Clift et al (2002), <sup>6</sup>Clift et al (2004), <sup>7</sup>Clift et al (2019), <sup>8</sup> (Zhou et al, 2021), <sup>9</sup>Feng et al (2021),  
732 <sup>10</sup>Alizai et al (2011).

733 **Figure 4:** Ar-Ar mica data plotted against depositional age for new (asterisked) and published samples.  
734 Note: <sup>1</sup>Published data from <sup>1</sup>Clift et al (2004) for modern Indus River data at Thatta, <sup>2</sup>published data  
735 from Najman et al (2003) for lower Chinji Formation, <sup>3</sup>published data from Najman et al (2003) for the  
736 Kamliyal Fm, and <sup>4</sup>published data from Najman et al (2001) for the Murree Formation at HKS. Apart from  
737 the lower Chinji Formation sample, Chinji and Nagri Formation samples are not tied to the  
738 magnetostratigraphically dated section (Johnson et al 1985, section 2.2.1), and therefore the  
739 depositional age range of these samples is shown by the grey bars. Note that Murree Formation samples  
740 are plotted on the y axis at the age of their MDAs.

741 **Figure 5:** schematic figure showing expected and actual changes in provenance characteristics of  
742 sedimentary archives upstream and downstream of the confluence, at the time when the Punjabi  
743 tributary system joins the palaeo-Indus trunk river, superimposed on the modern geology. More detail  
744 on analytical values summarised in this figure can be found in Table 1. Abbreviations: Av – average, Z –  
745 zircon, Eoc – Eocene, KLIA – Kohistan-Ladakh Island Arc.

## 746 **Tables**

747 **Table 1:** comparison of provenance data from the peripheral foreland basin with those from the Lower  
748 Indus Axial Basin and Indus Fan. Source region signatures also provided. Note that three “Mid Eocene”  
749 data points from the Indus Fan are omitted as the age was noted as questionable in the original  
750 publication of Clift et al (2001).

751 \*Compiled source region data from Ahmad et al. (2000); Bignold and Treloar (2003); Clift et al. (2019);  
752 DeCelles et al. (2004); DeCelles et al. (2016b); Deniel et al. (1987); Gehrels et al. (2011); Ji et al. (2009);  
753 Khan et al. (1997); Khan et al. (2004); Khan et al. (2009); Mahéo et al. (2009); Miller et al. (1999);  
754 Najman (2006); Pan et al. (2014); Richards et al. (2005); Robinson et al. (2001); Whittington et al. (1999);  
755 Zhang et al. (2004); Zhu et al. (2012); Zhuang et al. (2018), and additional references as listed in Fig S3b.

## 756 **Supplementary information**

757 **Text S1:** detailed analytical methodologies and sample information

758 **Table S1:** Sr-Nd bulk mudstone data.

759 **Table S2:** detrital zircon U-Pb data.

760 **Table S3:** White mica Ar-Ar analyses.

761 **Figure SI 1:** Sr-Nd mixture modelling of end members (A), and new (asterisk) and previously published  
762 bulk rock data from the peripheral and axial foreland basins in Pakistan, and the Indus Fan, plotted on to  
763 a sub-region of Fig A (B). Downstream published data: <sup>1</sup>Roddaz et al (2011), <sup>2</sup>Zhuang et al (2015), <sup>3</sup> Clift  
764 et al. (2001), Clift and Blusztajn (2005), Clift et al. (2019), Zhou et al 2021, and <sup>4</sup>Feng et al (2021). Means  
765 and one standard errors are calculated from compiled data points (same symbols with smaller sizes and  
766 transparency) (Zhuang et al., 2015 and references therein). HKS = Hazara-Kashmir Syntaxis; MHS =  
767 Murree Hill Station.

768 **Figure SI 2a and b** – KDEs for new and published zircon U-Pb data, at two different scales, 0-400 Ma and  
769 0-500 Ma. New data are shown by asterisks. Published data: <sup>1</sup>Alizai et al (2011) , <sup>2</sup>Clift et al (2022), <sup>3</sup>Ding  
770 et al (2016), <sup>4</sup>Qasim et al (2018), <sup>5</sup>Awais et al (2021).

771 **Figure SI 3:** MDS plot showing zircon U-Pb data for our new samples (asterisk) from the peripheral  
772 foreland basin (this study, red crosses), compared to downstream published data from the Kirthar and  
773 Sulaiman ranges (purple crosses, sample prefixes SR and Z, data from Roddaz et al, 2011 and Zhuang et  
774 al. 2015) and Indus Fan (data from Clift et al. 2019, Zhou et al 2021, Feng et al, 2022), grey crosses for  
775 Western Fan, black crosses for Eastern Fan. Also shown are published data from the modern Indus River  
776 upstream at Attock and downstream at Thatta (blue crosses, see Fig 1 for location, from Alizai et al 2011  
777 and Clift et al. 2022), and end member source signatures (black hexagons for Asian plate and arc, KLA =  
778 Kohistan-Ladakh Island arc, KK = Karakoram, HK = Hindu Kush, and red squares for Indian plate  
779 TH=Tethyan Himalaya, GH = Greater Himalaya, LH = Lesser Himalaya. References for compiled end  
780 member data are listed in Fig 3I 3b.

781 **Fig SI 4a and b** – KDEs for new and published mica Ar-Ar data from the peripheral foreland basin,  
782 Pakistan, at two different scales, 0-500 Ma and 0-100 Ma. New data are asterisk, published data is  
783 referenced on the plot.

784

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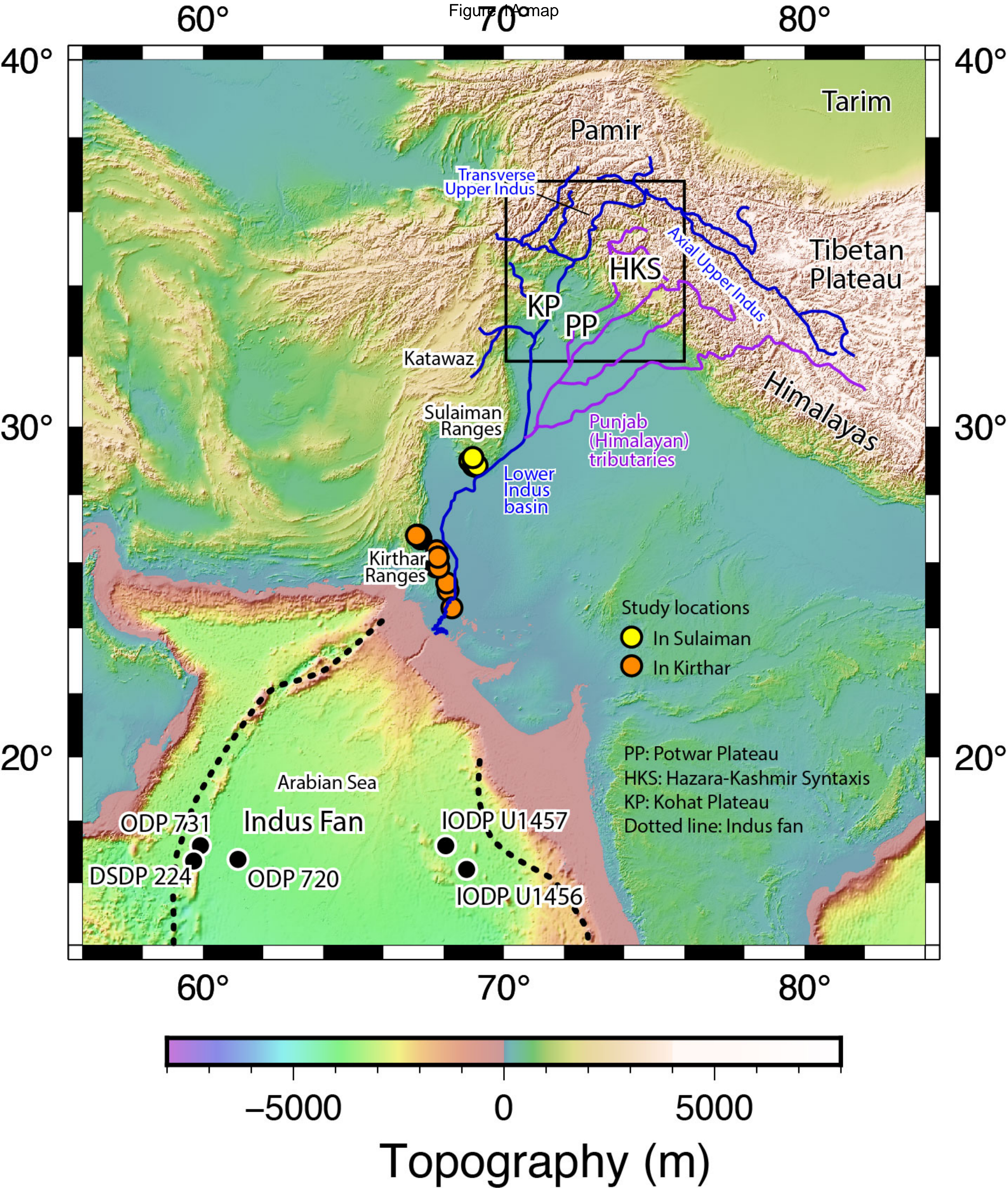
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1061

Terrane/ Basin Stratigraphy	$\epsilon Nd$	Zircons % with U-Pb ages 40-200 Ma (arc-derived)
<b>Source region characteristics*</b> (GHS, LHS, THS = Greater-, Lesser-, Tethyan Himalaya respectively; NP = Nanga Parbat)		
<b>Karakoram</b>	Average: -10	Dominant 40-200 Ma populations with some older grains to Precambrian
<b>Kohistan Island arc</b>	Average: +5	Entirely 40-200 Ma
<b>Indian plate</b>	Avg: -15 (GHS), -22 (LHS & NP), -11 (THS)	Near 100% > 200 Ma.
<b>Upstream peripheral foreland basin</b> (new & published data of <sup>1</sup> Clift et al 2002, <sup>2</sup> Alizai et al., 2011 and Clift et al 2022, <sup>3</sup> Ding et al 2016, <sup>4</sup> Qasim et al 2018)		
Modern Indus River	<i>No data for downstream of GHS</i> <sup>1</sup> At Skardu (upstream of GHS) -8.6 <sup>1</sup> At Besham (just into GHS) -10.7	<sup>2</sup> At Attock: 53% arc
Upper Miocene Nagri Fm	-9.4, -9.9	67% arc
Mid Miocene Chinji Fm	-7.7, -8.7 (our data). Chirouze et al., (2015) data: -3.8 to -7.7	47% arc
L-mid Miocene Kamlial Fm	-8.3	51% arc
Lower Miocene Murree Fm	-13.8 (MHS) -8.1, -9.2 (HKS, Paras north of Balakot)	23% arc (MHS) 50% arc (HKS, Paras north of Balakot) <sup>3</sup> 0-4% arc (HKS, Balakot) <sup>3</sup> 0-17% (HKS Muzaffarabad)
Lower-mid Eocene Kuldana Fm	-8.1, -8.8	<sup>3</sup> 49-75% arc (HKS, Balakot) <sup>3</sup> 6-74% arc (HKS, Muzaffarabad) Qasim Murree Hill station <sup>4</sup> 34-78% arc (MHS)
<b>Downstream Lower Indus axial basin, Kirthar (K) and Sulaiman (S) regions</b> ( <sup>1</sup> Clift et al. 2002, <sup>5</sup> Clift et al. 2004, <sup>6</sup> Roddaz et al 2011, <sup>7</sup> Zhuang et al. 2015)		
Modern Indus River	-15 <sup>1</sup> (below Sutlej confluence and at delta)	<sup>5</sup> At Thatta: 18% arc
Pliocene Siwalik Gp	-12 (K <sup>7</sup> ) n=2	12% arc (K <sup>7</sup> )
U. Miocene Siwaliks	-9.3 (K <sup>7</sup> ) n=1	
M. Miocene Siwalik Gp & Vihowa Fm	-11 (K <sup>7</sup> ) n=8	22% arc (K <sup>7</sup> )
L. Miocene Vihowa & Chitarwata Fms.	-10.5 (S <sup>6</sup> ) n=2, -13.1 (K <sup>7</sup> ) n=5	
Upper Oligocene Chitarwata Fm	Upper upper Oligocene -11.1 (S <sup>6</sup> ) n=3 Lower upper Oligocene -12.4 (S <sup>6</sup> ) n=3	
Lower Oligocene Chitarwata Fm	-9.6 (S <sup>6</sup> ) n=1; -13.4 (K <sup>7</sup> ) n=1	16% arc (K <sup>7</sup> ); 16% arc (S <sup>6</sup> )
L-mid Eocene Ghazij & Kirthar Gps	Av.-9.3 (S <sup>6</sup> ) n=2, -7.5 (K <sup>7</sup> ) n=1	
<b>Indus Fan</b> ( <sup>8</sup> Clift et al 2001 ; <sup>9</sup> Clift & Blusztajn 2005; <sup>10</sup> Clift et al 2019 ; <sup>11</sup> Feng et al. 2021 ; <sup>12</sup> Zhou et al. 2022).		
Pliocene	<sup>9</sup> Av. -10.8 (n=8)	<sup>10,12</sup> 19-32%
Miocene	<sup>8,10,11</sup> Av. -10.1 (n=47)	<sup>10,11,12</sup> 11-48%
Oligocene	<sup>8,10</sup> Av. -11.9 (n=16)	<sup>11</sup> 16-43%
M. Eocene	<sup>8</sup> -11.96, -5.2	
E. Eocene	<sup>9</sup> -9.3	

Figure 1A map



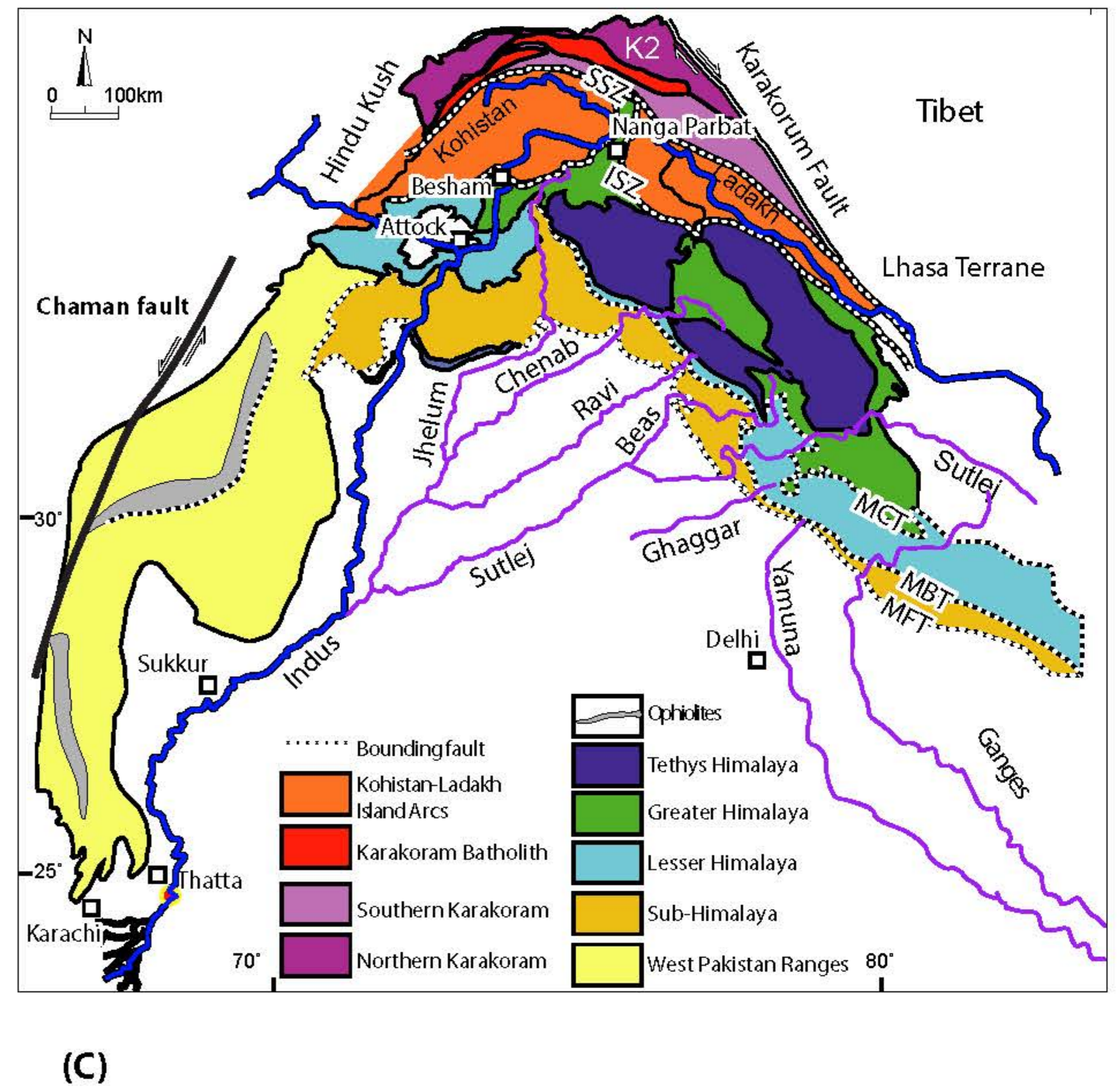
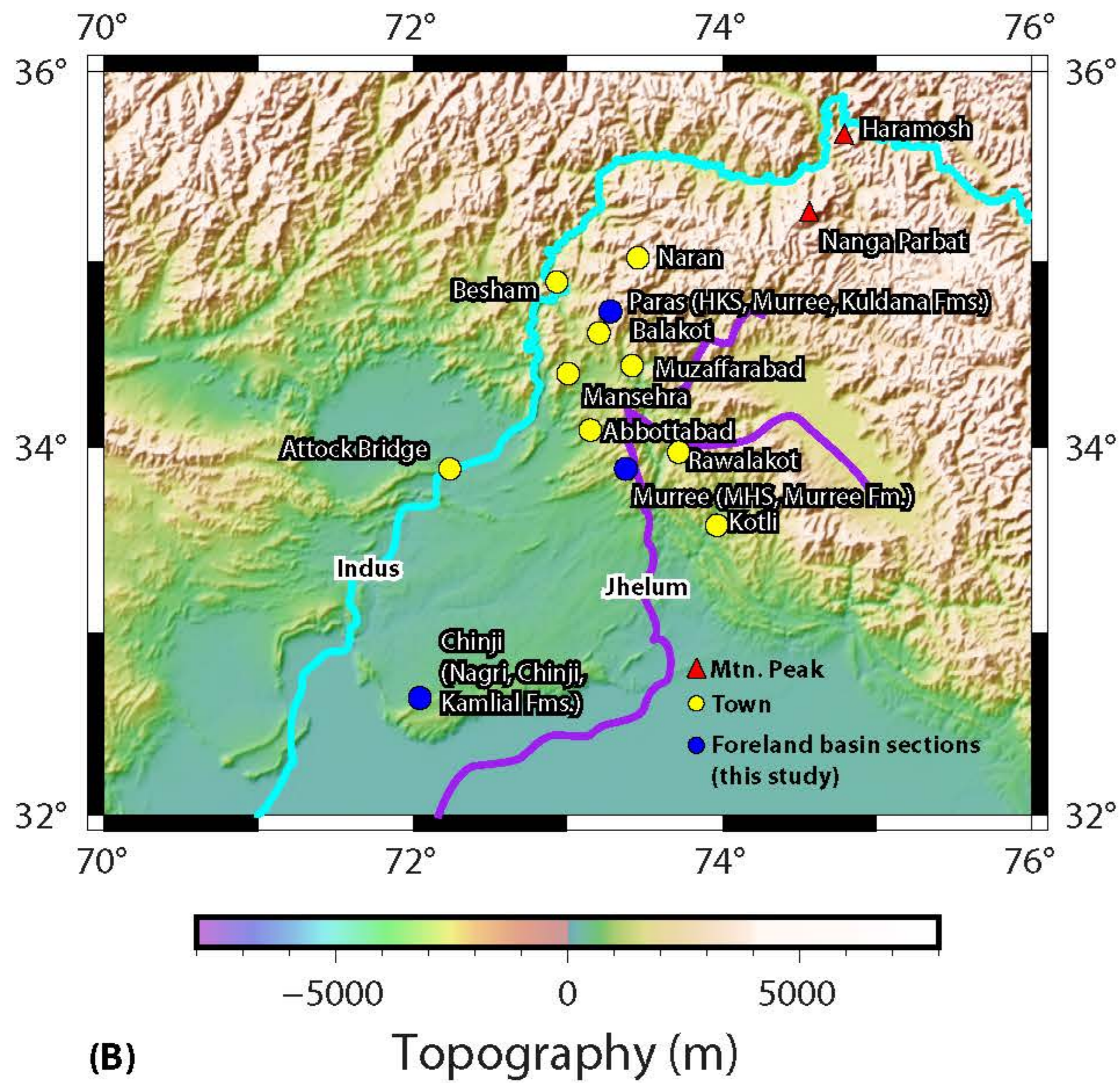


Figure 2 eps Nd against stratigraphic samples mean

(n = 9; this study, excluding the Murree Fm at MHS)

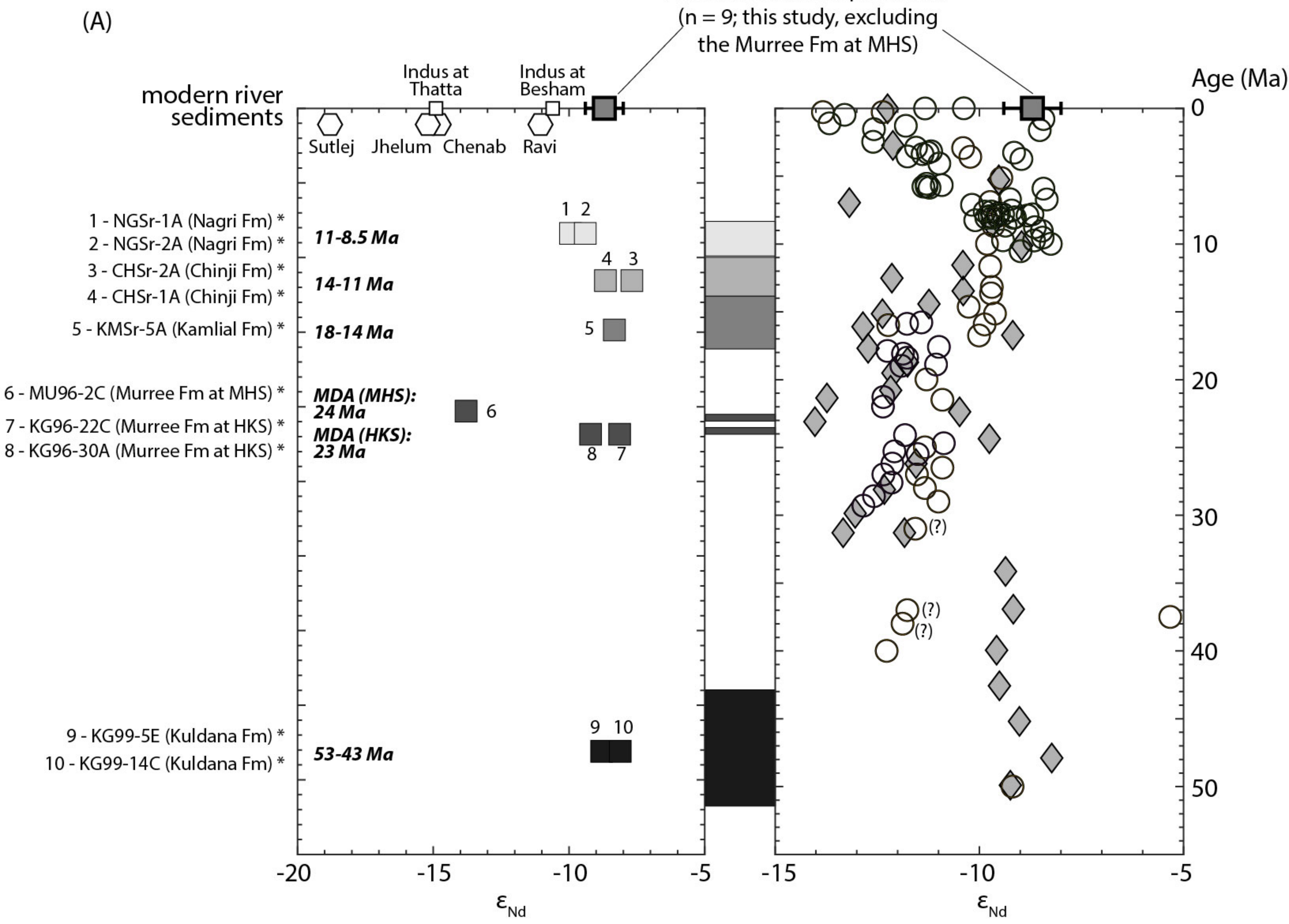


Figure 3 Zircon U-Pb cumulative plot

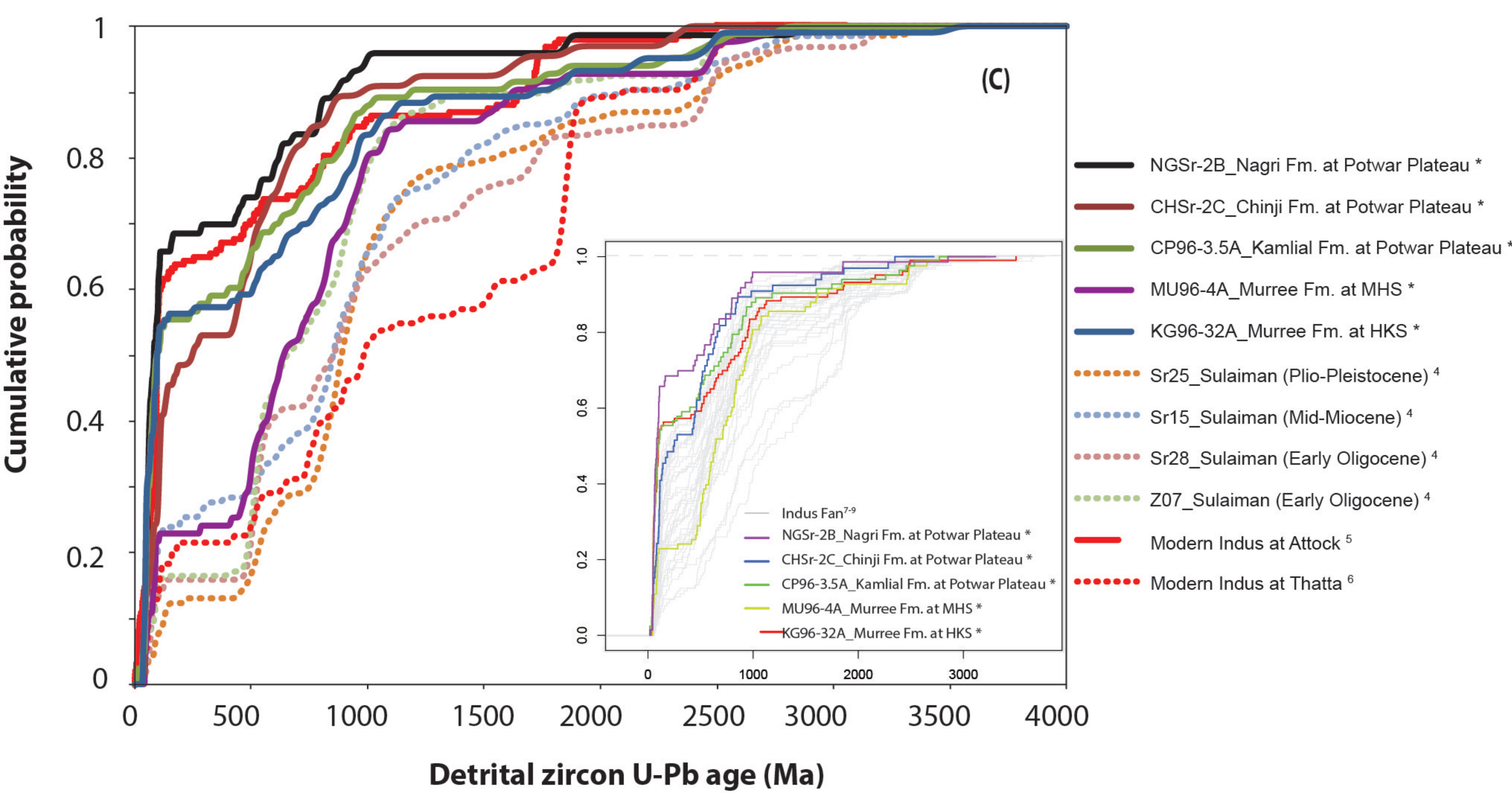
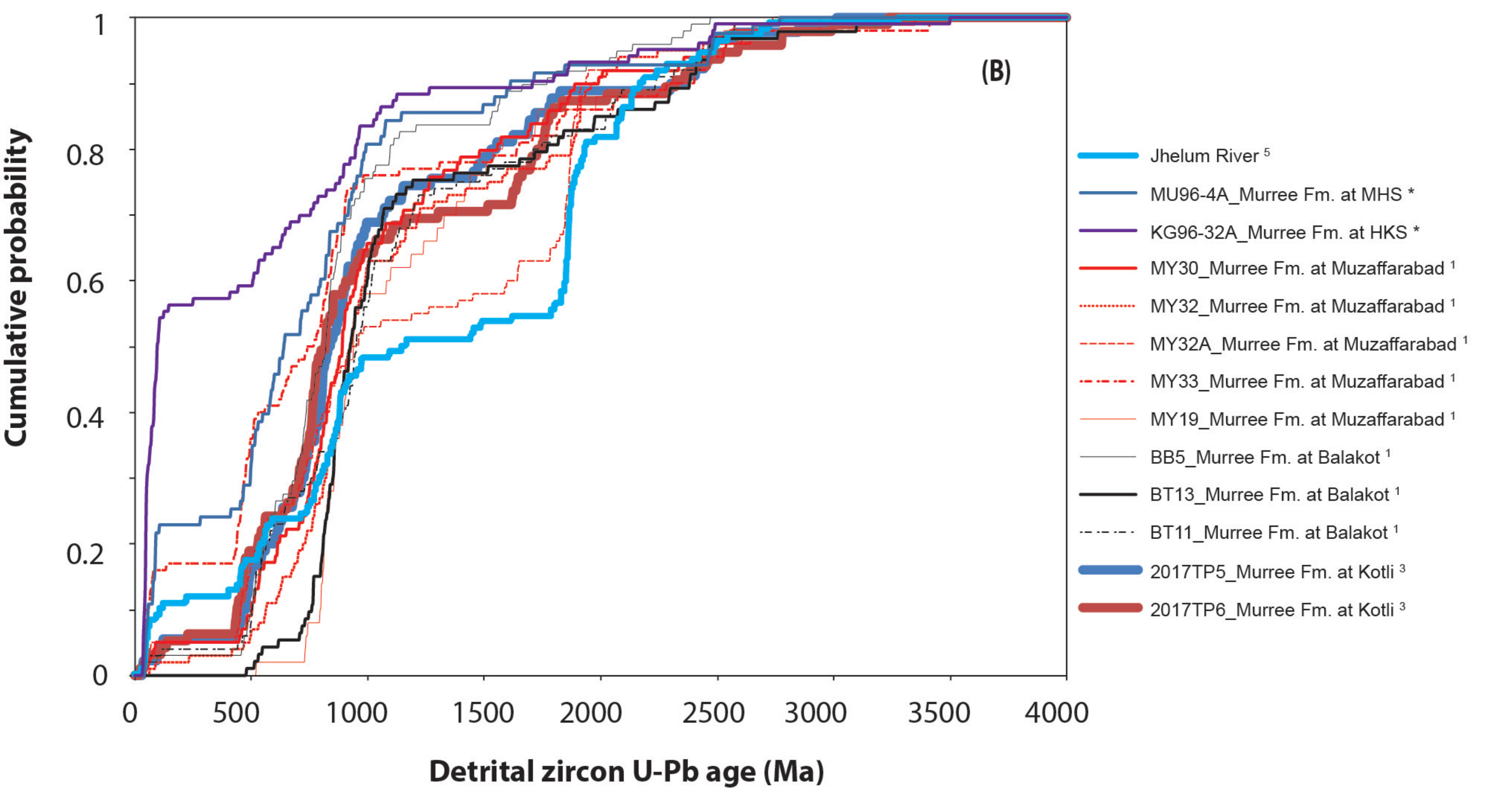
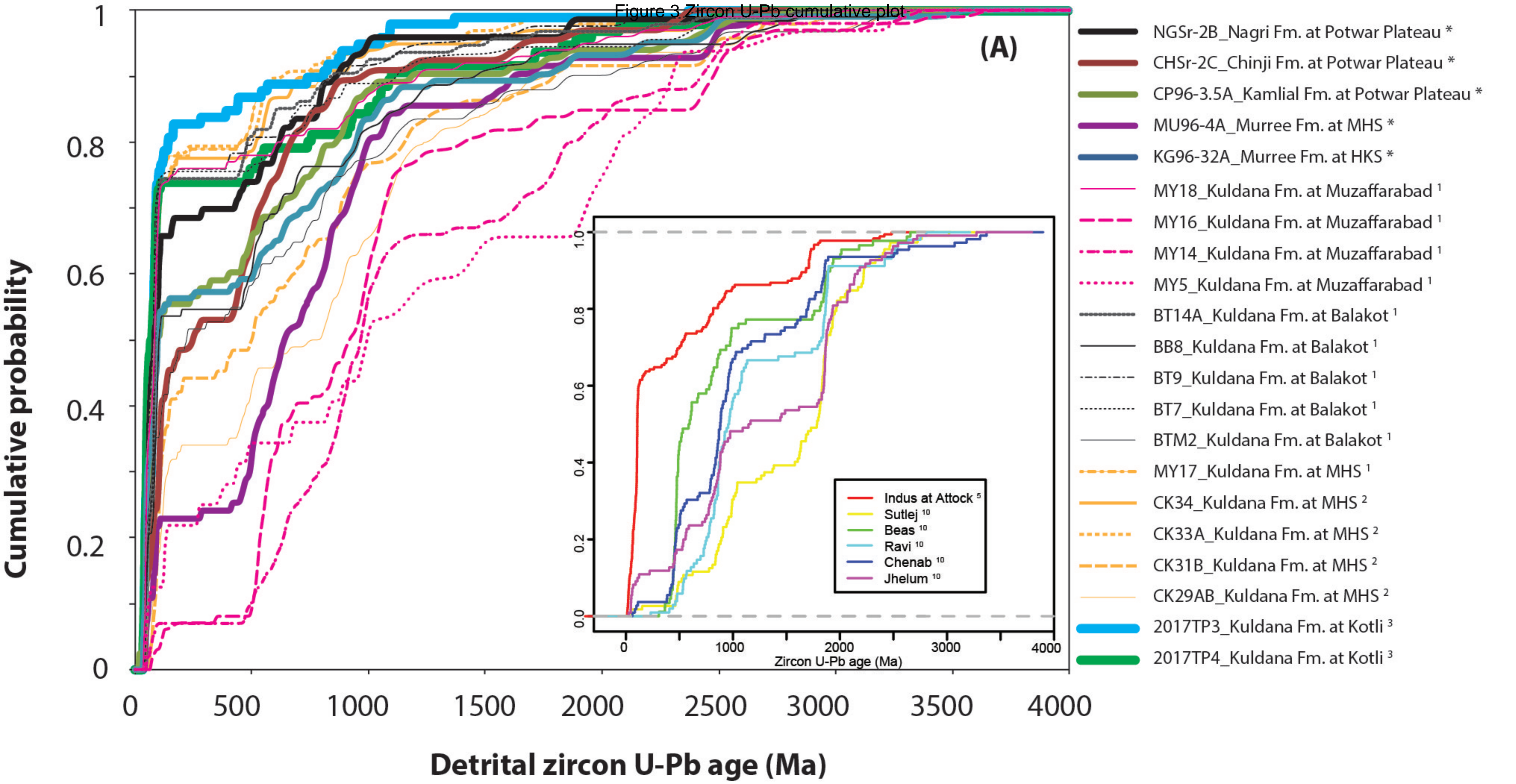


Figure 4 mica Ar-Ar lag time plot

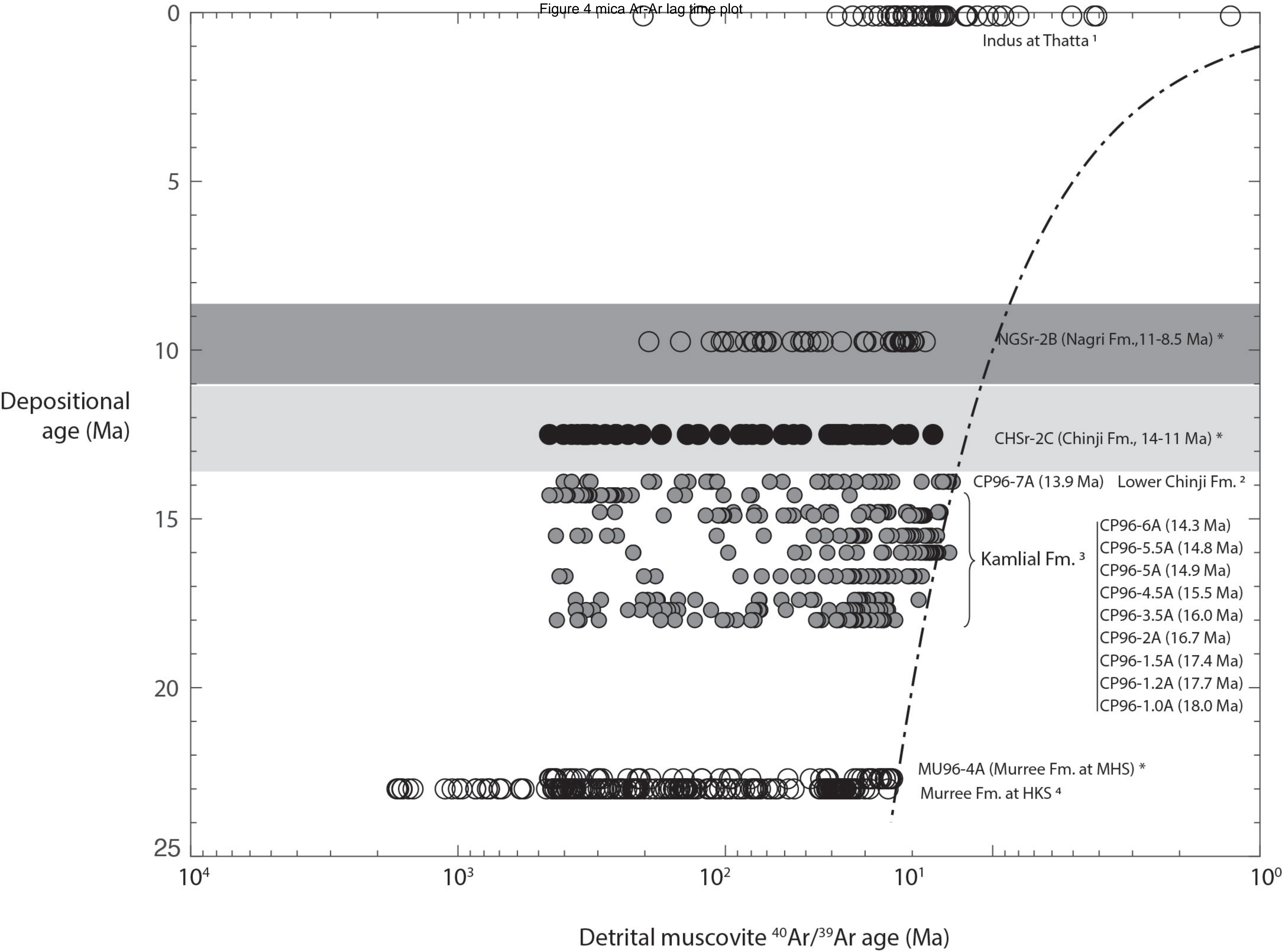




Figure 5 schematic palaeodrainage

