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Rapid exhumation since at least 13 Ma in the Himalaya recorded by detrital apatite fission-track dating of Bengal fan (IODP Expedition 354) and modern Himalayan river sediments

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(Article begins on next page)

1 **Rapid exhumation since at least 13 Ma in the Himalaya recorded by detrital**  
2 **apatite fission-track dating of Bengal fan (IODP Expedition 354) and**  
3 **modern Himalayan river sediments**

4  
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23 **Keywords:** Bengal fan, Himalayan rivers, Siwaliks, detrital apatite fission-track data, lag  
24 time, exhumation, erosion, threshold hillslope

26 **Abstract**

27           Apatite fission-track analysis of middle Bengal fan sediments (IODP expedition 354)  
28 and modern Himalayan river sediments shows that most of the detrital apatites are very young  
29 compared to their depositional ages, independent of their uranium content. Bengal fan apatites  
30 display an average central age lag time as short as  $2.26 \pm 1.6$  Myr since at least  $\sim 13$  Ma. Such  
31 lag times reflect a mean exhumation rate on the order of at least 1-3 km/Myr. The occurrence  
32 of detrital apatites with relatively short AFT lag times since           at least 13 Ma indicates that  
33 there have always been areas of rapid erosional exhumation, supplying detrital apatites to the  
34 fluvial system and delivering them to the paleo-Ganges and/or –Brahmaputra plains and  
35 finally to the Bengal fan. It also supports that temporary storage of detrital apatites in the  
36 floodplains or delta has always been negligible since at least 13 Ma. Comparison of the AFT  
37 data of the Bengal fan with those of the Central and Eastern proximal Neogene Himalayan  
38 foreland basin shows that both paleo-Ganga and –Brahmaputra catchments provided apatites  
39 with similar short lag time to the distal Bengal Fan basin.

40 In the modern drainage system of the Bengal fan, the apatites with young fission-track cooling  
41 ages are principally derived from areas where the topography has a sharp relief controlled by  
42 threshold hillslope processes and stream power resulting in landslide erosion as a coupled  
43 response to tectonic and fluvial forcing. By analogy with the modern erosion processes in the  
44 Himalayan range, we suggest that over the past 13 Ma, apatites were mainly derived from  
45 areas of sharp relief, where river stream power was high and hill slopes close to the threshold  
46 angle. As the exhumation signal is rather consistent since the late Miocene the detrital apatite  
47 fission-track data are either not sensitive enough to detect rapid climatically controlled  
48 changes in exhumation rates, or overall long-term erosion rates on the orogen scale are not  
49 strongly affected by climatic variations such as the variability of the Indian Summer Monsoon.  
50 Given the already rapid exhumation rates controlled by tectonics, the impact of climate

51 variability on surface erosion rates cannot be detected with our data, especially in the case of  
52 erosion processes dominated by threshold hillslope model.

53

## 54 **1. Introduction**

55 Understanding the dynamics of convergent mountain building, the sequence of thrusting  
56 and rates of erosional exhumation are crucial for understanding crustal deformation and for  
57 studying the influence of sediment flux on ocean geochemistry or tectonic and climatic  
58 coupling. The rate at which rocks are exhumed by erosion and the derived sediment  
59 transported to adjacent sedimentary basins is at the centre of studying the relationship between  
60 tectonic and surface processes in orogenic mountain belts. Given the large volume of  
61 particulate materials delivered by the Ganges and Brahmaputra rivers to the Indian Ocean at  
62 least since the Late Eocene – Oligocene (Najman et al., 2008), the study of Himalayan  
63 mountain building is of prime interest (Fig. 1A). Geological field studies provide a valuable,  
64 but partial, record of Himalayan mountain building. The mineralogical, isotopic and  
65 thermochronological analysis of Neogene sedimentary rocks provide a complementary dataset  
66 that records the unroofing history of the Himalaya, either from the proximal Siwaliks foreland  
67 basin (e.g. DeCelles et al., 2001, Huyghe et al., 2001; Bernet et al., 2006; van der Beek et al.  
68 2006, Chirouze et al., 2013), or the Bengal fan turbidite deposits at the ODP 116 and DSDP  
69 218 sites (e.g. Corrigan and Crowley, 1990; Copeland and Harrison, 1990; Galy et al., 1996;  
70 Galy et al., 2010).

71 Thermochronology of detrital grains in modern rivers or ancient sediments allows estimating  
72 present-day or paleo-exhumation rates from the lag times between the apparent cooling age  
73 and the depositional age of the detrital material in the river, the foreland basin or on the  
74 submarine fan (e.g. Cervený et al., 1988). Using apatite fission-track (AFT) low-temperature

75 thermochronology, the exhumation record from the Siwalik foreland basin and modern river  
76 deposits is restricted to the period of the past ~7 Ma because post-depositional partial  
77 annealing of fission tracks in apatites affected AFT ages in deeply buried sedimentary rocks  
78 (van der Beek et al., 2006; Chirouze et al., 2013). The Bengal fan presents a thinner, more  
79 condensed, Neogene section, and therefore much less buried, which allows extending the  
80 exhumation back to the mid-Miocene (Corrigan and Crowley, 1990). Here we present AFT  
81 data of twenty-three new detrital samples from the <20 Ma record of the Bengal fan at 8°N in  
82 the Indian Ocean collected in 2015 during the IODP expedition 354 (Fig. 1A; France-Lanord  
83 et al., 2016). In addition, AFT data from six new modern river samples are also presented,  
84 together with published data from two other rivers in order to decipher the detrital record  
85 linked to the present-day Himalayan exhumation pattern (Fig. 1A).

86 In this paper, we show that detrital apatite with young fission-track ages and short lag times  
87 dominate the Bengal fan sediments back to at least 13 Ma, similar to the exhumation signal  
88 seen in the river sediments. This implies that fast exhumation, at least in some of the  
89 Himalayan hinterland domains existed since at least that time. By analogy with the modern  
90 system, we propose that erosion is mainly controlled by sharp relief, where river stream power  
91 was high and hill slopes close to the threshold angle. As the method that we use for the  
92 acquisition of the AFT in the Bengal Fan is similar to that used in the Siwalik foreland basin  
93 of Central and Eastern Himalaya, we compare the two exhumation records. Therefore, we  
94 suggest that source rocks from Central and Eastern Himalaya equally contributed to the AFT  
95 short lag time recorded in the Bengal Fan. Finally, we discuss the impact of climate variability  
96 on surface erosion rates.

97

## 98 **2. Geological setting**

100 The collision between the Indian and Asian plates began during late Paleocene - early  
101 Eocene times along the Indus-Yarlung suture zone (IYSZ), which juxtaposes the pre-collision  
102 Indian passive margin sequence to the south with the Cretaceous-Paleogene Andean-type  
103 Asian Transhimalayan batholiths and ophiolites to the north (e.g. Hu et al., 2015). South of  
104 the IYSZ, the Main Himalayan Thrust (MHT) accommodated convergence (e.g. Bollinger et  
105 al., 2006 and references herein), generating the Himalayan structure that consists of four major  
106 lithotectonic units delimited by north-dipping faults branching off the basal MHT. From north  
107 to south, these faults are the South Tibetan detachment, which separates the Neoproterozoic to  
108 Eocene Tethyan Sedimentary Series from the high-grade metasedimentary rocks and granites  
109 of the Greater Himalayan sequence. The Main Central thrust separates the Greater Himalayan  
110 sequence rocks from low-grade metasedimentary rocks of the Lesser Himalayan sequence.  
111 The Lesser Himalayan thrust system places the Lesser Himalayan rocks over the Siwalik  
112 Group clastic rocks of the Neogene foreland basin, which in turn were thrust over the  
113 Ganges and Brahmaputra alluvial plains along the Main Frontal thrust. East and West of the  
114 Himalayan arc, the Namche Barwa and the Nanga Parbat syntaxes, respectively, constitute  
115 north-south trending antiformal structures exposing high-grade metamorphic rocks of Indian  
116 origin (e.g. Zeitler et al., 2001; Seward and Burg, 2008).

117 The long-term exhumation of the Himalayan range has already been recorded since  
118 ~12 Ma by low-temperature thermochronometers such as zircon fission track (ZFT) or white  
119 mica  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  dating of detrital grains preserved in the Siwalik sediments of Western, Central  
120 and Eastern Himalaya (e.g. Cervený et al., 1988; Bernet et al., 2006; Szulc et al., 2006;  
121 Chirouze et al., 2013). From *in situ* thermochronological data, rapid exhumation is evidenced  
122 in localized areas (e.g. Blythe et al., 2007; Seward and Burg, 2008; Robert et al., 2011; Thiede  
123 & Ehlers, 2013). Different tectonic processes are inferred to control exhumation: 1) 20°-30°

124 north dipping mid-crustal ramps affecting the rather flat MHT and localized surface uplift of  
125 the hanging wall (e.g. Bollinger et al., 2006); 2) active thickening occurs within portions of the  
126 orogenic wedge (Whipple et al., 2016) and is partly related to 3) out-of-sequence steep faults  
127 merging the basal thrust system (e.g. Hodges et al., 2004). At deeper levels, the ductile  
128 behaviour of the crust also controls zones of localized exhumation (Vannay et al., 2004). It has  
129 been suggested that a major zone of exhumation existed at the leading edge of a channel flow  
130 (e.g. Godin et al., 2006) that also involved the brittle levels located above the exhumed deep  
131 levels (4 on Fig. 1B). The viscous behaviour of the deep level favours rock motion out of the  
132 convergence direction and rapid exhumation in the Himalayan syntaxes (Zeitler et al., 2001; 5  
133 on Fig. 1B). Slab dynamics has also been inferred to control much of the tectonic deformation  
134 of the Himalayan orogenic wedge (Mugnier and Huyghe, 2006; Webb et al., 2017). As these  
135 different tectonic interpretations are still debated, most researchers agree that localized surface  
136 uplift and exhumation processes result in physiographic sharp increases of the Himalayan  
137 relief with mean elevations above 6000 m and increasing erosion rates (Burbank et al., 2003;  
138 Hodges et al., 2004; Elliott et al., 2016). In these zones and altitudes, the kinetics of  
139 weathering and soil development are thought to be far less important than the bedrock uplift  
140 rates and erosion occurs through landsliding, which increases nonlinearly until being equal to  
141 river incision (Larsen and Montgomery, 2012) and hillslope angles approaching the threshold  
142 angle (e.g. Burbank et al., 2003).

## 143 *2.2. The modern Bengal Fan catchment*

144 The modern Ganges catchment includes the Himalayan lithotectonic units described above.  
145 The modern Brahmaputra watershed also encompasses units from the IYSZ and from the  
146 Transhimalayan batholiths. Indo-Burmese Range material and the Precambrian Indian  
147 basement of the Mikir Hills/Shillong Plateau and its Tertiary sedimentary cover may also

148 slightly contribute to the sediment load of the Brahmaputra River (Lupker et al., 2017 and  
149 references therein).

150 The modern Ganges and Brahmaputra catchments provide respectively about  $390 \pm 30 \times$   
151  $10^6$  and  $400-1160 \times 10^6$  tons/yr of sediment to the Bengal Fan (Lupker et al., 2017 and  
152 references therein). Overall present-day erosion rates of 0.7 to 1.2 mm/yr and 1.0-1.1mm/yr on  
153 the  $10^3-10^4$  years time scale for respectively the entire Tsangpo-Brahmaputra and Ganga  
154 catchments have been deduced from  $^{10}\text{Be}$  analyses of detrital quartz of river sands (Lupker et  
155 al., 2017). Such rates may differ from long-term average exhumation rates derived from  
156 detrital apatite or zircon fission track data. The Lesser and Greater Himalayan domains are  
157 locally exhumed with mean rates of about 1.8 mm/yr and up to 5 mm/yr, respectively, based  
158 on detrital AFT and ZFT data and *in situ* AFT (Bernet et al., 2006; van der Beek et al., 2006;  
159 Blythe et al., 2007; Thiede and Ehlers, 2013 and references therein). North of the IYSZ, the  
160 Transhimalayan batholiths had a very episodic history of erosion with some intervals with less  
161 than 0.3 mm/year and others exceeding 4 mm/year (Copeland et al., 1987) whereas the  
162 Namche Barwa syntaxis experiences exhumation at rates of up to 5-10 mm/yr (e.g. Seward  
163 and Burg, 2008). Therefore the exhumation of the Himalaya varies in time and space: fast  
164 exhumation rates only occur in some locations of the Himalaya (e.g. Thiede & Ehlers, 2013)  
165 and are then greater than the average erosion rates.

166

### 167 **3. Sampling**

168 The IODP Expedition 354 drilled the Bengal fan at  $8^\circ\text{N}$  (Fig. 1A). This study is based  
169 on the deepest sites (U1450) and (U1451) which reached  $\sim 800$  m and  $\sim 1200$  m below sea  
170 floor respectively (Table 1), recovering Quaternary to Paleogene turbidite and hemipelagic  
171 sediments (France-Lanord et al., 2016). The samples consist of siltstones and fine-grained  
172 sandstones, corresponding to the coarsest basal parts of thick turbidites, stratigraphically dated



173 by the micro- and nanno-fauna present in the intercalated hemipelagic deposits. Mineralogical  
174 and geochemical analyses showed that the turbidite material has very strong affinity to sand  
175 and silt of the modern Ganges and Brahmaputra rivers and are therefore relevant for  
176 reconstructing erosion and changes in Himalayan hinterland source areas (France-Lanord et  
177 al., 2016). For this study, we use the stratigraphic age model established by France-Lanord et  
178 al. (2016) from the mean age of the nannofossils, foraminifera and Chrons acquired onboard  
179 refined for the <1.9 Ma deposits by the magnetostratigraphic model of Reilly (2018). The  
180 uncertainty in the depositional > 1.9 Ma ages is taken as the difference between the mean age  
181 from France-Lanord et al. (2016) and the age of the youngest fauna considering that older  
182 fauna in turbidite horizons could be recycled from previously deposited sediments on the fan,  
183 resulting in a depositional age estimates that is too old.

184 In addition, eight modern river sand samples from the Ganges-Brahmaputra catchment  
185 have been used in this study, six new samples (Fig. 1A, Table 2), and published detrital AFT  
186 data of the Kameng and Rangit river samples were taken from Chirouze et al. (2013) and  
187 Abrahami et al. (2016) respectively.

188

#### 189 4. **Apatite Fission-Track analysis**

190 Apatite is an accessory mineral and only represents about one in every 1000 detrital  
191 grains in the Ganges and Brahmaputra sands (Garzanti et al., 2010), but it can be readily found  
192 in river and marine sediments, and the Bengal fan turbidites (Corrigan and Crowley, 1990).  
193 Even though the fraction is small for most samples sufficient apatite crystals were recovered  
194 for fission-track dating. We used the 80-160  $\mu\text{m}$  fraction of fine-grained sandstone for AFT  
195 analysis. Apatite grains were separated using standard heavy liquid and magnetic separation  
196 techniques. Apatite aliquots were mounted in epoxy, polished to expose internal crystal  
197 surfaces, and etched for 20 s at 21°C with 5.5 M  $\text{HNO}_3$ . All samples were covered with

198 muscovite mica sheets as external detectors and sent for neutron irradiation to the FRM II  
199 Research Reactor at the Technische Universität München in Garching, Germany. Apatite  
200 samples were irradiated together with IRMM540R dosimeter glasses (15 ppm U) and Durango  
201 and Fish Canyon Tuff age standards.

202         After irradiation the mica sheets of all samples and standards were etched for 18 min at  
203 21°C in 48% HF. All datable grains, including zero-track grains, within a mount were included  
204 in the analysis. Grains were selected for dating primarily on their orientation parallel to the c-  
205 axis and on the basis of the grain images in the mica detectors. The samples and standards  
206 were counted dry at 1250x magnification, using an Olympus BX51 optical microscope and the  
207 FTStage 4.04 system of Trevor Dimitru. The objective was to date up to 100 grains per  
208 sample, when that was possible, depending on available sample material and grain quality.

209

#### 210         *4.1 Track count statistics and zero-track grains*

211         The precision of AFT grain ages depends on track counting statistics. The more  
212 induced and spontaneous tracks can be counted, the smaller the individual grain age  
213 uncertainty becomes (Galbraith, 2005). As we used the external detector method for AFT  
214 dating in this study, one needs to be aware that the formation of induced tracks recorded in the  
215 mica detectors of the unknown samples, age standards and the dosimeter glasses also have  
216 Poisson distributions. This is why track counts of spontaneous and induced tracks for samples,  
217 standards and dosimeter glasses are taken into account for calculating age uncertainties (see  
218 age and error equations in Galbraith, 2005). In our sample set from the Bengal fan and the  
219 river samples a particular challenge is to deal with a large number of apatites that do not  
220 contain any (zero-track grains) or only very few (<4) spontaneous fission tracks. If a grain has  
221 zero, one, two or three spontaneous fission tracks it may either have a very young apparent  
222 cooling age or a very low U concentration, or both. Young low U concentration grains tend to

223 have large age uncertainties. This can result in apparent cooling age estimates that are younger  
224 than the depositional age without being affected by partial annealing. The true but unknown  
225 and poorly constrained cooling age of such apatite grains may well be older than the age of  
226 deposition of these grains,. In order to evaluate single grain ages of such grains we not only  
227 provide the single grain ages, but also the 95% confidence intervals in which most likely the  
228 true cooling age of each single grain lies (Galbraith, 2005). The 95% confidence intervals for  
229 each grain age were calculated with the Binomfit program of M. Brandon. In addition, for all  
230 samples central and minimum ages were calculated using the RadialPlotter program of  
231 Vermeesch (2009). The central age is an estimate of an average fission-track age of a grain-  
232 age distribution, which may be heavily over-dispersed, whereas the minimum age is an  
233 estimate of the youngest coherent grain-age population within a detrital grain-age distribution  
234 (Galbraith, 2005).

235         Given the relatively low closure temperature of the AFT thermochronometer (~110°C  
236 for F-OH apatite (e.g. Reiners and Brandon, 2006), and the ~60-110°C AFT partial annealing  
237 zone (PAZ) temperature range, depending on mineral chemistry and holding time within the  
238 PAZ, existing fission tracks may be progressively annealed after deposition (e.g. Reiners and  
239 Brandon, 2006). In the case of the Bengal fan most apatites are F-rich, a result already  
240 obtained by Corrigan and Crowley (1990).

241

#### 242         4. 2 *Exhumation rate estimations*

243         As the main objective of this study was to estimate rates of exhumation from the  
244 detrital AFT data, we decided to use the minimum age approach (Galbraith, 2005 and  
245 references herein), instead of the more commonly used binomial peak-fitting approach, which  
246 was applied in previous studies on the Siwaliks Formation (van der Beek et al. 2006; Chirouze  
247 et al., 2013). For most samples this does not make a big difference, as in many cases the

248 minimum age and the first peak determined by binomial peak-fitting are identical or do  
249 overlap at the 95% confidence level. Nonetheless, applying the minimum age model avoids  
250 sample size (number of grains) bias to younger ages (Galbraith, 2005). Therefore, for the  
251 samples that fail the  $\chi^2$  homogeneity test and that have a considerable (>20%) dispersion of  
252 their single grain age distribution, the minimum age provides a more reliable estimate of the  
253 first coherent age population (Galbraith, 2005). The minimum age lag time can provide an  
254 estimate on the fastest exhumation rates in the source area, with the lag time being defined as  
255 the difference between the apparent AFT age and the depositional age (e.g. Bernet et al.,  
256 2006). The same calculation can be done with the central ages for an estimate on mean  
257 exhumation rates. In the absence of post-depositional partial annealing, the lag time integrates  
258 the time between cooling of the apatite below the fission-track closure temperature in the  
259 source rock, exhumation towards the surface, erosion, sediment transport in the fluvial system,  
260 and deposition in the Bengal fan. For the Himalaya, transport times can be considered as being  
261 negligible (Lupker et al., 2017), and the lag time is considered as a direct measurement of  
262 erosional and tectonic exhumation within the source area at the time of deposition. We use a  
263 1D thermal advection model (Appendix D) to obtain first-order estimates of average  
264 exhumation rates from our AFT lag-time data.

265

## 266 **5. Apatite fission-track results**

### 267 *5.1. Bengal fan turbidites*

268 Twenty-three samples from 17.7 to 1153.4 m below sea floor and respectively from 0.3 to 17.2  
269 Ma stratigraphic age were analysed (Table 1). The results show the typical wide range of non-  
270 reset detrital grain ages between 0.2 Ma and about 70 Ma with central ages ranging between  
271 0.9 and 14 Ma and minimum ages between 1.7 and 12.1 Ma (Fig. 2). Most of the samples fail  
272 the  $\chi^2$  test and show large grain age dispersions of >30% (see Appendix B for the details of

273 every samples). For the four samples that do pass the  $\chi^2$  test only 30 or less grains could be  
274 dated. A total of nineteen samples have central ages equal or older than the depositional age at  
275 the 95% confidence level. Central and minimum AFT ages are also regularly older in deeper  
276 and stratigraphically older sediments (Fig. 2). For the site U1450, one sample displays both  
277 central and minimum ages younger than the modelled age of deposition. For the deeper site  
278 U1451, eight samples have their central and minimum ages younger than their deposition ages,  
279 of which six samples are within their 2-sigma error range overlapping with the depositional  
280 age (Table 1). The peculiar results of these samples are discussed below. For both sites U1450  
281 and U1451, the difference between the central and the minimum ages of the Bengal fan  
282 samples is on average less than 1.5 Myr and for many samples both age estimates overlap at  
283 the 95% confidence level.

284 Radial plots and cumulative grain age plots with the single grain 95% age confidence intervals  
285 have been performed (Figs. 3 and 4 and Appendix B). Finally, the age-U concentration  
286 relationship indicates that many of the grains with <2 Ma apparent AFT cooling ages have U  
287 concentrations in the 10-100 ppm U range (Fig. 5).

288

## 289 *5.2. Himalayan modern river sand apatite fission-track data*

290 New AFT ages of river sediments of the Brahmaputra, Siang, Sun Kosi, Daraundi Khola,  
291 Marsyandi, and Bothe Kosi rivers are shown in Table 2. Grain ages of the Himalayan river  
292 sands range between 0.2 Ma and about 48 Ma. The older, Eocene ages are found in the Siang  
293 and Marsyandi rivers only. All the eight Himalayan river samples fail the  $\chi^2$  test (Appendix  
294 C). Central ages of the Himalayan river sand samples vary between  $1.2 \pm 0.2$  Ma and  $4.6 \pm 0.5$   
295 and minimum ages range between  $0.66 \pm 0.66$  (Rangit River) to  $3.7 \pm 1$  Ma (Fig. 6 and Appendix  
296 B).

297

298

## 299 **6. Discussion**

300 Young AFT cooling ages are widely documented from *in situ* bedrock studies (e.g. Blythe  
301 et al., 2007; Thiede and Ehlers, 2013), which reinforce our findings. Below, we first detail and  
302 comment on the samples for which have AFT ages younger than the depositional ages (Table  
303 1). We then give the implications of young AFT and short lag time ages for the long-term  
304 exhumation rates in the Ganga-Brahmaputra catchment, for the erosion processes providing  
305 young detrital apatites to the drainage system and finally its implications regarding  
306 tectonic/erosion/climate interactions over the last 13 Ma.

### 307 *6.1 Interpreting apatite fission-track ages based on low track counts*

308 The AFT age versus U concentration plot of the Bengal fan sediments shows that AFT cooling  
309 ages of <2 Ma are not restricted to grains with very low (<10 ppm) U concentrations. The  
310 same observation may be done from the detrital apatites carried by the modern Himalayan  
311 rivers (Fig. 5). Nonetheless, the interpretation of AFT ages based on low (<4) spontaneous  
312 tracks per grain, is difficult.

313 One could first argue that the low spontaneous track counts of the samples with younger AFT  
314 ages than their depositional age is related to post-depositional partial annealing because of  
315 reheating caused by burial heating and/or hydrothermal fluid flow. Given that 1) the sediments  
316 were collected from <1200 m below seafloor, and 2) the maximum depositional age is ~16 Ma  
317 (Fig. 2), partial annealing of fission-tracks in apatite would be highly unlikely if the basin  
318 geothermal gradient is not in excess of ~100°C/km. Present-day thermal gradients measured  
319 during IODP Expedition 354 are on the order of 40°C/km (France-Lanord et al., 2016),  
320 consistent with ocean basins of same age of 90–100 Ma and other values measured in the Bay  
321 of Bengal (Hasterok et al., 2011). For such a geothermal gradient, the 60-100°C AFT partial  
322 annealing zone is reached from burying depth of 1500 m, which is not the case for the

323 concerned samples (Table 1 and Fig. 2). In addition, the occurrence of smectite and the  
324 absence of illite rich smectite-illite mixed-layered clay minerals within the clay mineral  
325 fraction of the turbidites sampled for AFT analysis (France-Lanord et al., 2016), independently  
326 suggests that temperatures of partial annealing were never reached. Smectite starts to turn into  
327 illite at temperatures of 70-95°C (Lanson, 1995), which corresponds to the upper part of the  
328 AFT partial annealing zone (e.g. Reiners and Brandon, 2006). Therefore we have to consider  
329 another explanation for their young AFT ages.

330 Samples with only few apatite (<30 grains) may present central or minimum ages younger  
331 than the depositional age (table 1). Sample U1450A 110F is an example for this situation (Fig.  
332 3) and only 26 single grain could be analysed with 19 grains with zero spontaneous tracks, and  
333 6 with only 1 or 2 spontaneous tracks, leaving only 1 grain with >2 spontaneous tracks  
334 (Appendix B). An additional interesting observation is that the minimum age of this sample is  
335 older than the central age, being drawn up by the one older grain, with the highest U  
336 concentration (Fig. 3). The central and minimum ages of this sample have relatively large  
337 uncertainties. Less than 30 grains were also analysed for samples U1451A 74F4 and U1451B  
338 51R2 generating AFT age uncertainties greater than those for samples with more grains  
339 counted (Fig. 3). Therefore, we do not consider those samples in the following.

340 At site U1451, more samples with minimum and/or central ages younger than the  
341 depositional age (negative lag times) can be observed especially for the deepest samples (Fig.  
342 2 and Table 1). Sample U1451A 37F2, has central and minimum ages younger than the  
343 depositional age of  $6.53 \pm 0.3$  Ma. For this sample 74 grains were dated, but 32 of these grains  
344 (43%) have very low (<4) spontaneous track counts (see Appendix B), which skew the  
345 minimum and central ages to younger values, as grains with higher track counts of this sample  
346 result in ages older than the depositional age (Fig. 4). Therefore, we will not consider this  
347 sample in the following discussion and exclude these results in respect of our interpretation.

348 Samples U1451A 86F2, U1451B16 R1, U1451B 27R1, U1451B 37R2 and U1451B 45R1 all  
349 have minimum or central AFT ages that overlap with the 2-sigma error range with their  
350 depositional ages (Table 1). Sample U1451A 86F2 has ~20% of the 70 grains dated with <4  
351 spontaneous tracks, sample U1451B 16R1 42% of 100 dated grains, sample U1451B 27R1  
352 19% of 69 grains dated, sample U1451B 37R2 46% of 59 grains dated and sample U1451B  
353 45R1 68% of 89 grains (Appendix B). The radial plot of U1451B 45R1 shows that higher U-  
354 concentration grains have younger apparent cooling ages (Fig. 4C). The lowermost sample  
355 U1451B 58R2W with a depositional age of  $17.2\pm 0.5$  Ma and a 1046.89 m burial depth, has  
356 minimum and central ages that are considerably younger than the depositional age (e.g.  
357 negative minimum age lag times of  $8.2\pm 5.1$  Myr), as shown in Table 1. For this sample only  
358 32 grains could be dated of which 38% have low spontaneous track counts.

359

360 One can also note that from 550m in the U1451 site (Fig. 2), turbidite main granulometry is  
361 finer and composed of clayey silt instead of fine sands in the upper stratigraphic levels and in  
362 site U1450, making the sampling of apatite grain more difficult and less abundant. Therefore,  
363 the stratigraphically lowermost samples just show the importance of obtaining as many single  
364 grain ages as possible from high track density grains if available to get more tightly  
365 constrained age estimates.

366 Our analysis underlines that the AFT dating method reaches its detection limits when dealing  
367 with grains that have low spontaneous track counts and low U concentrations.

## 368 *6. 2. Detrital Apatite fission-track signal and modern erosion in Himalaya*

369 The average AFT central age value is  $2.53\pm 0.28$  Ma and  $2.9 \pm 0.39$  for the rivers draining  
370 respectively the Central and Eastern Himalaya, which are the rivers belonging to the Ganga or  
371 Brahmaputra catchment (Fig. 7). The river sediments, which were obviously collected much  
372 closer to their source areas than the Bengal fan sediments, provide a faithful representation of



373 the *in situ* bedrock AFT age distribution in the source (e.g. Thiede and Ehlers, 2013 and  
374 references therein), suggesting a very short transit and delivery time from the source to the  
375 sink. Such a short transit time is also reflected by the late Quaternary Bengal Fan AFT  
376 samples, the AFT central ages of which are very similar to the Himalayan rivers AFT ages  
377 discussed above (Table 2, Figs. 5-7) and suggests almost no transient storage in both the  
378 fluvial plain and delta.

379         Young *in situ* AFT ages (Burbank et al., 2003; Blythe et al., 2007; Whipple et al.,  
380 2016) are either found in zones close to and north of the sharp topographic transition (Fig. 1B)  
381 of the Greater Himalaya domain (Thiede and Ehlers, 2013 and references therein), or in the  
382 Namche Barwa and Nanga Parbat syntaxial antiforms (e.g. Zeitler et al., 2001; Seward and  
383 Burg, 2008). Although the exhumed areas are narrow, laterally discontinuous, and located on  
384 the southern side of the Himalaya, they provide the youngest apatite to the river system  
385 (Thiede and Ehlers and references therein). Seven out of eight rivers have central ages of 3 Ma  
386 or less (Table 2 and Fig. 7), for the rivers draining the sharp topographic transition and higher  
387 Himalayan relief. Therefore the influence of these areas is significant with respect to sediment  
388 input to the rivers. The dominance of apatite with about 2-3 Ma fission-track ages is enhanced  
389 because the formations north of the sharp topographic transition mainly consist of the apatite-  
390 richer Greater Himalayan Sequence (Robert et al., 2011). Focused exhumation of the steep  
391 Namche Barwa syntaxis, with young AFT cooling ages (0.7-1.1 Ma *in situ* AFT ages; Seward  
392 and Burg, 2008), is also significantly contributing to the Brahmaputra River (AFT minimum  
393 and central ages of respectively  $2.61 \pm 0.83$  Ma and  $3.05 \pm 0.39$  Ma) close to its confluence with  
394 the Ganges River.

395         The detrital AFT age value for the rivers are averaging different source areas, and the  
396 small average difference for rivers draining the Central and Eastern Himalaya strongly suggest  
397 a near impossibility to distinguish the provenance (Central or Eastern Himalaya) of detrital

398 apatite in the Bengal fan sediments (Fig. 7). Additional information, which would allow  
399 distinguishing different source rocks, would be needed. Nonetheless, in both cases, the apatites  
400 originate from areas with steep slopes of sharp relief, which are exhumed rapidly.

401 Exhumation rates are significantly correlated with high stream power and landslide  
402 erosion rates along steep slopes in the Namche Barwa massif (Larsen and Montgomery, 2012).  
403 Similarly, the high exhumation rates evidenced in central Himalaya by younger than 2 Ma *in*  
404 *situ* AFT ages (e.g. Robert et al., 2011) correlates with a sharp topographic relief displaying  
405 steep slopes close to a  $\sim 33^\circ$  threshold angle (Hodges et al., 2004) and strongly incised by river  
406 channels with a high stream power (Lavé and Avouac, 2001). Almost  $\sim 14\,000$  landslides  
407 induced by the 2015 Gorkha earthquake are located close and to the north of this  
408 physiographic transition between Higher and Lesser Himalaya domains and are characterized  
409 by slopes greater than  $35^\circ$  (e.g. Tsou et al., 2018). Therefore the exhumation of the youngest  
410 detrital AFT population found downward of these zones is controlled by a threshold hillslope-  
411 model of erosion, where landscape evolution is linked to landslide erosion, tectonic uplift,  
412 fluvial forcing and efficient sediment evacuation.

### 413 *6.3. Long-term exhumation signal from apatite fission-track data*

414 The main observation drawn from the Bengal fan AFT data in this study is the  
415 occurrence of apatite with central AFT ages having lag times averaging  $2.26 \pm 1.6$  Myr) since  
416 the mid-Miocene (Table 1, Fig 7). These short lag times imply that some Himalayan source  
417 areas were rapidly exhumed at least at rates of 1 to 3 mm/yr, as estimated from a 1D thermal  
418 advection model for fluor apatite (Appendix D).

419 Previous studies in the proximal Siwalik foreland basin deposits of the Central  
420 Himalaya (van der Beek et al. 2006), and Eastern Himalaya (Coutand et al., 2016 and  
421 Chirouze et al., 2013) indicate AFT data ages that mainly range from 0.3 to 35 Ma. The

422 Bengal Fan and Siwalik data were acquired with a similar method. We compare below the  
423 central AFT ages already published in the Siwaliks with the Bengal Fan AFT central ages (as  
424 central and minimum ages overlap at 95% confidence level). For the last 6-7 Ma (older AFT  
425 data in the Siwaliks are subjected to partial annealing), the mean lag time for the Central and  
426 Eastern Siwaliks are respectively  $2.47 \pm 1.7$  Myr and  $2.13 \pm 1.44$  Myr while it is of  $2.19 \pm 1.6$  Myr  
427 from the Bengal Fan turbidites. These results are therefore very similar and overlap at  $2\sigma$   
428 level, although the catchment basin of the Bengal Fan is much greater and may contain older  
429 sources than the ones of the Central and Eastern Siwalik domains (Fig. 7 and Tables 3 and 5).  
430 This suggests that sources have been rapidly exhumed in both central and eastern catchments  
431 from 6-7 Ma. Provenance analysis of the apatite should provide the litho-tectonic localisation  
432 of young apatite and how the exhumation varies in space and time, but this is not beyond the  
433 scope of this study. The lack of post depositional partial annealing for the Bengal Fan AFT  
434 data allows extending the record of exhumation back to 13 Ma. It shows that for the period 7-  
435 13 Ma, young apatite were also provided by the main Himalayan rivers, indicating that there  
436 has always been areas of rapid erosional exhumation, supplying detrital apatites to the fluvial  
437 system and delivering them to the paleo Ganges and/or Brahmaputra plains and finally to the  
438 Bengal Fan. The rate of such a rapid exhumation might not correspond to the same areas  
439 through time, but is relatively constant over the last 13 Ma. Another feature rising from this  
440 analysis is that the Siwalik foreland basin has been an overfilled basin since at least 13 Ma.  
441 Finally, the detrital apatite fission-track ages of the Bengal Fan turbidites display similar lag  
442 time characteristics to the AFT ages carried by present-day Himalayan rivers. Therefore, the  
443 processes described in the above section for the modern erosion in the Himalayan range could  
444 be extended in the past and we suggest that, over the last 13 Ma, apatite were mainly derived  
445 from areas of sharp relief, where river stream power was high and hill slopes close to the  
446 threshold angle.

448 *6.4. Detrital fission tracks and tectonic/erosion/climate interactions over the past 13 Ma*

449 It has been suggested that erosion of the Himalaya is enhanced by the intense monsoonal  
450 rainfall (e.g. Burbank et al., 2003) and that an east-west climatic gradient involving higher  
451 amount of precipitation and higher erosion in the east than in the west (e.g. Bookhagen and  
452 Burbank, 2010) controls the tectonics of the thrust wedge (e.g. Chalaron et al., 1995). Neither  
453 an east/west regional or a temporal evolution of the exhumation is visible in the detrital AFT  
454 data of the modern Himalayan rivers, in the Bengal fan deposits or in the Neogene Siwaliks  
455 foreland basin deposits of the central and eastern Himalaya (Fig. 7).

456 Marked differences in precipitation and seasonality occurred within the Bengal  
457 fan catchment over the past 13 Ma as suggested by stable carbon and oxygen isotopic studies  
458 (e.g. Dettman et al., 2001), and they might have modified the erosion of the Himalaya and be  
459 recorded in the sedimentary flux of the Bengal Fan (Krishna et al., 2016). Although these  
460 climate/erosion relationships remain an active debate for the global Plio-Pleistocene (e.g.  
461 Herman et al., 2013; Schildgen et al., 2018 and references therein) or for the late Miocene (e.g.  
462 Clift et al., 2008), the erosion of the Himalaya has increased at the onset of the Plio-  
463 Pleistocene Northern Hemisphere cooling (Herman et al., 2013) or in the Late Miocene  
464 affected by an intensification of monsoon (e.g. Clift et al., 2008). Although the sedimentary  
465 flux from the 12 Ma long stable drainage system (Galy et al., 2010) seems to reflect these  
466 events (Krishna et al., 2016), the AFT data (Fig. 7) do not reveal any significant variation in  
467 erosion rate. We suggest that this difference is linked to a mixing of material coming from  
468 different domains affected by different erosion rate. In this study the minimum ages of the  
469 AFT reflect the domains of the most rapid exhumation. The absence of a climatic signal in  
470 these data agrees with the predictions of the threshold hillslope model (e.g. Larsen and  
471 Montgomery, 2012), which is less sensitive to climatic variations, as rainfall only affects

472 erosion through variations of the river profiles (e.g. Whipple and Tucker, 2002), which are  
473 buffered by variations of the stream power due to changes in the river width (e.g. Lague,  
474 2013).

475 Therefore the detrital AFT data do not have the precision to trace the effect of climate-  
476 variability on exhumation rates on the <2 Myr timescale. In contrast, the persistence of detrital  
477 apatite with short AFT lag times in the Bengal fan sediments may be rather linked to the  
478 distribution of tectonically driven uplift on longer time-scales, and the morphology of the  
479 mountain belt. Given that exhumation within the main Himalayan orogen since at least 13 Ma  
480 propagated southward (Fig. 8) as suggested by A) the classical forward propagating thrust  
481 systems model of e.g. DeCelles et al., (2001 or Bollinger et al., (2006); and B) the  $\epsilon$ Nd studies  
482 performed in the Siwaliks of the Central Himalaya (e.g. Huyghe et al., 2001) and in the Bengal  
483 fan (Galy et al., 2010), the locus of rapid exhumation may have changed over time. Therefore,  
484 continuous rapid exhumation evidenced in the Bengal fan AFT data most likely reflects the  
485 underlying tectonic scheme driven by a permanent convergence between Asia and India and  
486 strong resulting uplift localized in limited areas such as the syntaxes or the hanging walls of  
487 crustal ramps.

488

489

## 490 **7. Conclusions**

491 Detrital AFT ages determined from turbidite deposits of the middle part of the Bengal  
492 fan provide a long-term record of Himalayan exhumation. Since at least 13 Ma, apatite grains  
493 with short minimum and central lag times (respectively  $1.55 \pm 3.13$  Myr and  $2.26 \pm 1.6$  Myr)  
494 were deposited in the Bengal fan. Apatite with such short lag times are also found in river  
495 sediments of the modern Ganges and Brahmaputra drainage system. Therefore, the lag time  
496 over the past 13 Ma and the modern lag time both support that temporary storage of detrital

497 apatite in the floodplains of the river drainage or in the delta are negligible and that  
498 exhumation rates have been consistently fast on the order of at least 1-3 km/Myr. Therefore,  
499 there have always been areas of fast erosion in the Himalayan range. Comparison of the AFT  
500 data of the Bengal Fan with those of the Central and Eastern proximal Neogene Himalayan  
501 foreland basin shows that both paleo Ganga and Brahmaputra catchments provided apatite  
502 with short lag time to the distal Bengal fan basin. Additional provenance analysis is needed to  
503 determine how such a fast exhumation varied in space and time.

504         The AFT data from the modern Himalayan erosion system show that apatites with  
505 short AFT lag times are derived from zones undergoing relatively rapid exhumation along the  
506 southern flank of the Himalaya. In these zones, the dominant processes of erosion are  
507 controlled by high stream power of the rivers that efficiently transport fluvial sediments and  
508 by a threshold angle triggering landslides and limiting the slope of the hills. Therefore, by  
509 analogy with the modern erosion processes in the Himalayan range, we suggest that over the  
510 past 13 Ma apatite were mainly derived from areas of sharp relief, where river stream power  
511 was high and hill slopes close to the threshold angle. Consequently, the maximum exhumation  
512 rate provided by the Bengal fan apatite were not strongly affected by climatic variations  
513 related by the onset of the Plio-Pleistocene Northern Hemisphere cooling or by the reported  
514 intensity changes of the Indian Monsoon. The maximum exhumation rates provided by the  
515 minimum and central ages of the AFT of the Bengal fan are characteristic of the tectonic  
516 processes at the Ma scale resolution.

517

518

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526

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## 690 **Figure captions**

691 Figure 1:

692 A) The Ganga-Brahmaputra catchment of the Bengal Fan (from Galy et al. 2010) - B: Bhopal;  
693 C: Kolkata; D: Delhi; K: Kathmandu; NBS: Namche Barwa Syntaxis; THB: Tran-Himalayan  
694 Batholiths. River names are those cited in the text and are indicated by the following symbols.  
695  $\alpha$ : SunKoshi,  $\beta$ : Brahmaputra;  $\chi$ : Subansiri;  $\delta$ : Rangit,  $\epsilon$ : Kameng,  $\phi$ : Marsyandi and  
696 Daraundi,  $\gamma$ : Bhote Kosi,  $\lambda$ : Karnali;  $\eta$ : Siang;  $\mu$ : Dibang;  $\rho$ : Rapti. Location of sampling is  
697 displayed by stars for apatites.

698 B): Sketch of the inferred structural elements of the Indo-Asia collision zone controlling  
699 localized rapid exhumation rates (orange, purple and red lines refer respectively to the 110°C  
700 isotherm related to the AFT closure temperature, to the brittle/ductile transition and to the  
701 750°C isotherm below which partial melt starts). In the brittle regime : 1) the Main  
702 Himalayan Thrust (MHT) is affected by a crustal ramp (e.g. Elliot et al., 2016) that migrated  
703 during the evolution of the range and delineates duplexes (e.g. De Celles et al., 1998); 2)  
704 internal shortening (Whipple et al., 2016) including 3) out-of-sequence thrust (Hodges et al.,  
705 2004); In the ductile regime (thin lines): distributed shearing (horizontal arrows) and vertical  
706 flattening define a channel flow (ChF) (Godin et al., 2013) with a fast exhumation zone (4) at  
707 its frontal edge and/or (5) a lateral extrusion in the syntaxes (e.g. Zeitler et al., 2001).

708 Figure 2: Variation of the AFT central ages (blue diamond) and AFT minimum ages (red  
709 square) versus depth for the two drilling sites U1450 and U1451 (Bengal Fan, 8°N).  
710 Horizontal bars correspond to  $2\sigma$  uncertainty. Red line represents the age model based on the  
711 magnetostratigraphic model of Reilly (2018) for the <1.9 Ma deposits and on polynomial  
712 extrapolation between shipboard and post-cruise biostratigraphic constraints based on  
713 nannofossil zones (France Lanord et al., 2016). The minimum age curve (grey dotted line) is  
714 established from the youngest fauna considering that older fauna in turbidite horizons could be  
715 reworking by the turbiditic current.

716 Figure 3: A) Cumulative AFT age plots, organized from youngest to oldest grains of selected  
717 samples showing the 95% age confidence intervals. Samples U1450A 24HG and U1450A  
718 110F with respectively 100 and less than 30 counted grains are shown for comparison of the  
719 robustness of AFT ages; B) Apatite fission-track age radial plots of corresponding Bengal fan  
720 samples, showing central and minimum ages determined with RadialPlotter (Vermeesch,  
721 2009). Radial plots and cumulative age plots of all samples are available in the Appendix B.

722 Figure 4: Radial plots of samples U1450A 6 7 8F (minimum and AFT central ages older than  
723 depositional age), U1451A 37F2 (minimum and AFT central ages younger than depositional  
724 age) and U1451B 45R1 (minimum and AFT central ages that overlap with the 2-sigma error  
725 range with its depositional age) are shown for comparison. Radial plot of sample U1451B  
726 45R1, displays a trend of apatite with younger cooling ages and higher U concentrations.

727 Figure 5: A) Single grain AFT age versus U concentration plot of detrital apatite grains of  
728 sample series U1450A and U1451A. B) Plot for apatite with fission-track cooling ages <2Ma).  
729 C) Single grain AFT age versus U concentration plot of detrital apatite grains from modern  
730 Himalayan river sediments. The red dotted line correspond(s) to 10 ppm U concentration  
731 below which grains are considered to have a poor U content.

732 Figure 6: AFT age radial plots of the new Himalaya river samples presented in this study,  
733 showing central and minimum ages determined with RadialPlotter (Vermeesch, 2009).

734 Figure 7: Comparison between Bengal Fan, Siwaliks and Himalayan rivers AFT central ages.  
735 Bengal Fan AFT data are represented by blue diamonds, Siwalik AFT data from Central  
736 Himalaya (Van der Beek et al., 2006) by squares and Siwalik AFT data from Eastern  
737 Himalaya (Chirouze et al., 2013, Coutand et al., 2016) by triangles. Yellow squares and  
738 triangles represent AFT central ages of Himalayan rivers belonging, respectively, to the Ganga  
739 and Brahmaputra rivers.

740 Figure 8: Relationships between sharp topographic transition in Himalaya, exhumation short  
741 AFT lag time and transport toward the proximal and distal Bengal Fan foreland basins. When  
742 the 110°C exhumation path of apatite crystals (green line), reaches the topography, erosion  
743 occurs and material containing apatite is shed to the river system (blue line and arrows) and  
744 finally to the Bengal Fan. Green circles indicate the FT central lag time (in Myr) of detrital  
745 apatites in the rivers running in the proximal foreland basin and in the Bengal fan distal basin;

746 green squares indicate the *in situ* age range of the apatite provided by the steepest slopes.  
747 Three sketches are drawn from the available AFT data: modern Himalaya, 6-7 Ma Himalaya,  
748 12-13 Ma Himalaya.  
749 A) sketch of the Bengal fan U1451 drill hole (from France-Lanord et al. 2016) recording short  
750 AFT lag times since 13 Ma. For caption of the drill hole lithology, see Figure 2.  
751 B) modern Himalayan sketch with sharp topographic transition above the ramp system and in  
752 the Namche Barwa syntaxis (NB). Recent AFT of the Bengal Fan and AFT of Himalayan  
753 rivers are from this paper. *In situ* AFT ages are from Burbank et al. (2003) and Blythe et al.  
754 (2007) above the Himalayan ramp system. *In situ* AFT ages are from Seward and Burg (2008)  
755 for the Namche Barwa syntaxis.  
756 C) sketch of the persistence of very steep mountain zones related to rapid exhumation zone in  
757 Himalaya from 6-7 Ma to the present-day, as suggested by the AFT of the < 6-7 Ma Siwalik  
758 and Bengal Fan sedimentary records (van der Beck et al., 2006; Chirouze et al., 2013; Coutand  
759 et al., 2016 and this study); D) sketch of the persistence of very steep mountain zones related  
760 to fast exhumation zone in Himalaya from 7 to 13 Ma (as suggested by the Bengal fan  
761 sedimentary record, this study). No indication is given for the paleo-Himalayan rivers as AFT  
762 of the Siwalik proximal basin are reset.

763

## 764 **Tables**

765 Table 1. Bengal fan detrital apatite fission-track data and central age lag-time estimates for  
766 samples from the IODP 345 sites 1450 and 1451

767 Table 2. Central and eastern Himalayan river detrital apatite fission-track data and sample  
768 locations

769

## 770 **Supplementary material:**



771 Appendix A: Details of composite samples of the Bengal Fan  
772 Appendix B: Bengal fan data set - Apatite fission-track single grain age data, Apatite fission-  
773 track radial plots and grain age 95% confidence interval plots  
774 Appendix C: Himalayan rivers data set - Apatite fission-track single grain age data and Apatite  
775 fission-track radial plots  
776 Appendix D: Lag time to exhumation rate relationship determined with the 1D thermal  
777 advection model Age2Edot of Brandon (see Ehlers et al. 2005) for F-apatites.  
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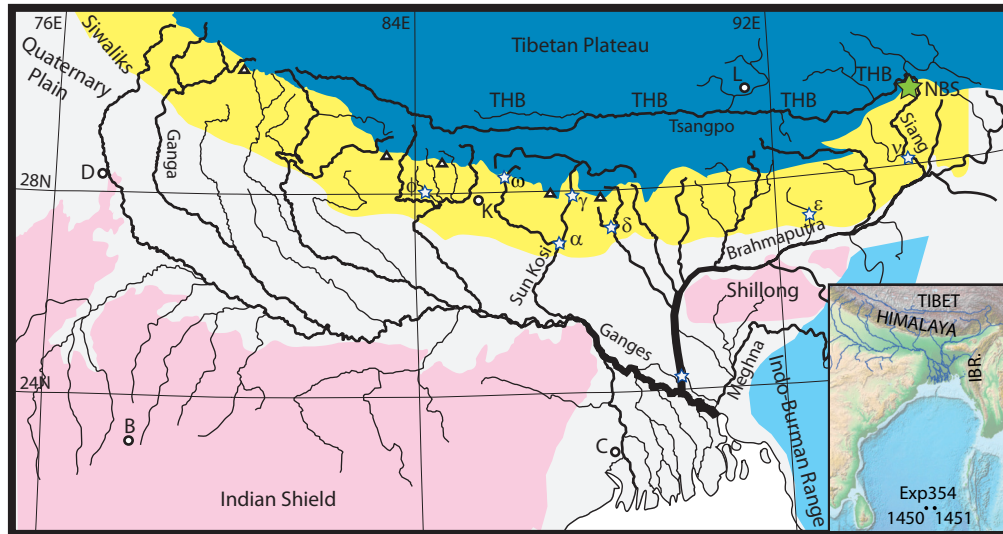


Figure 1a

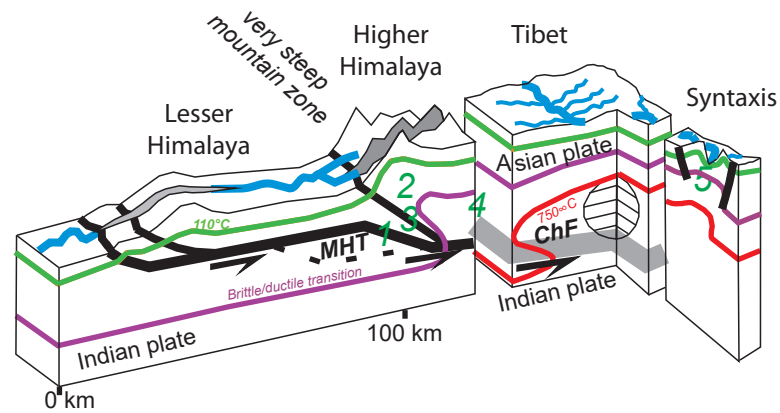
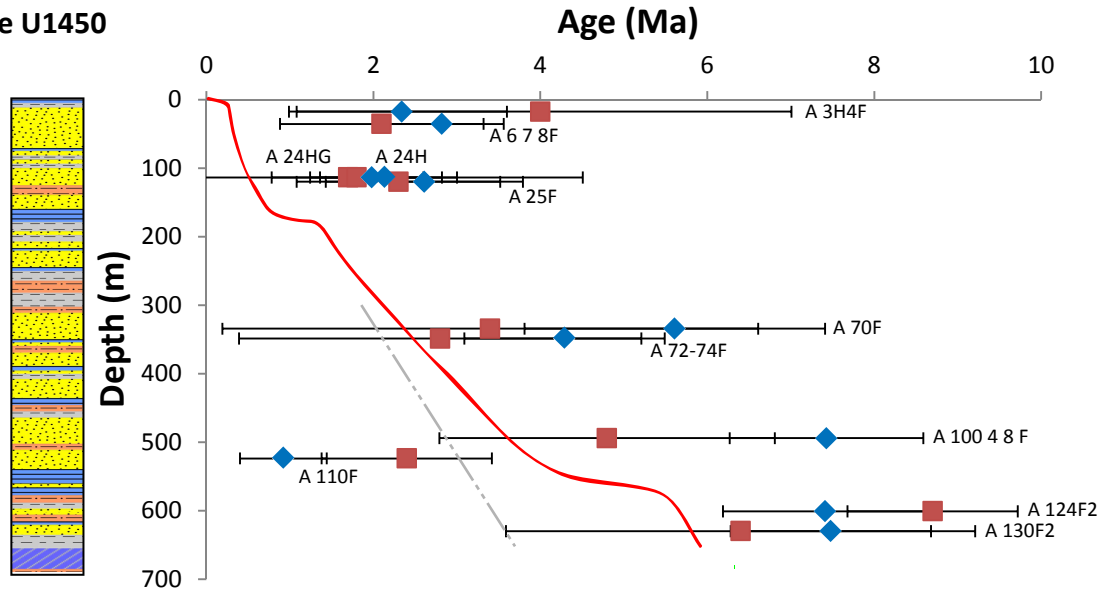


Figure 1b

Site U1450



Site U1451

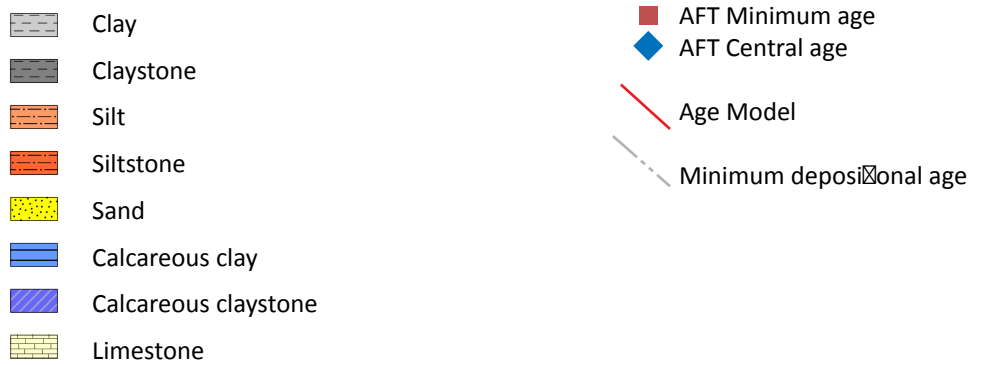
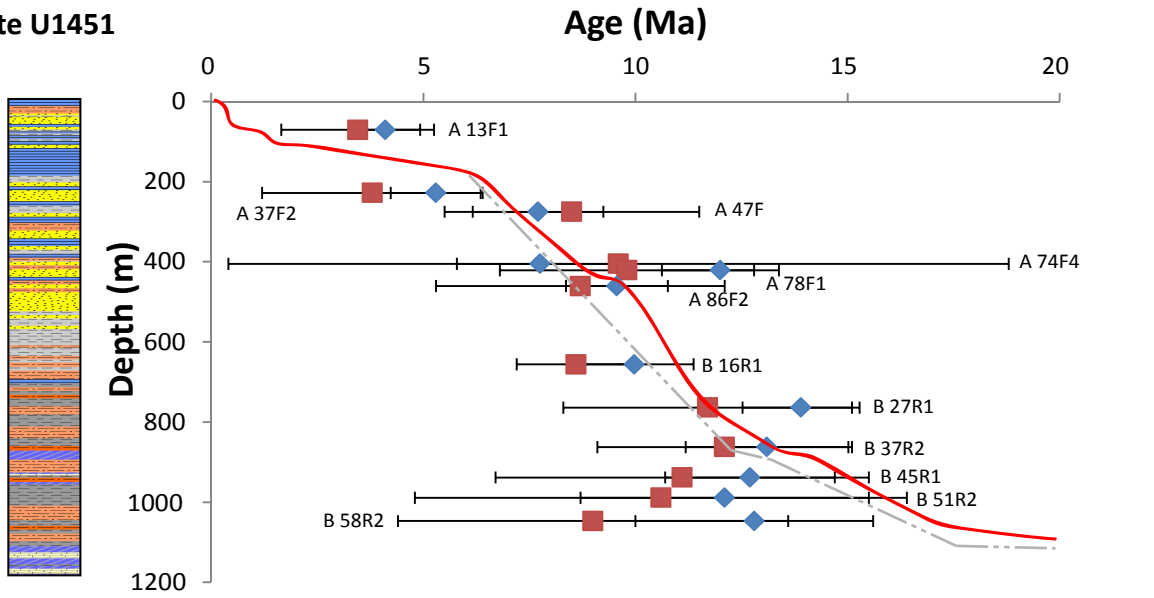


Figure 2

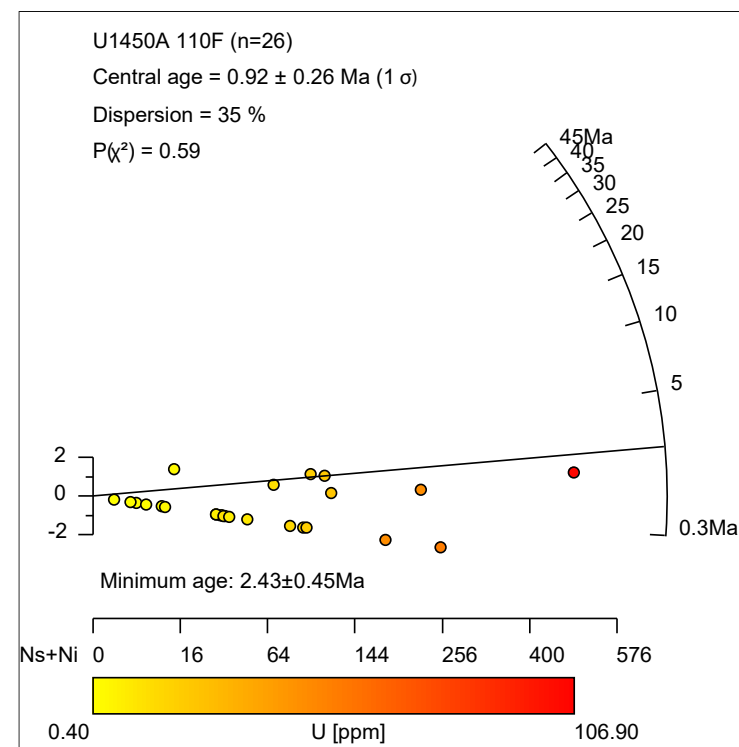
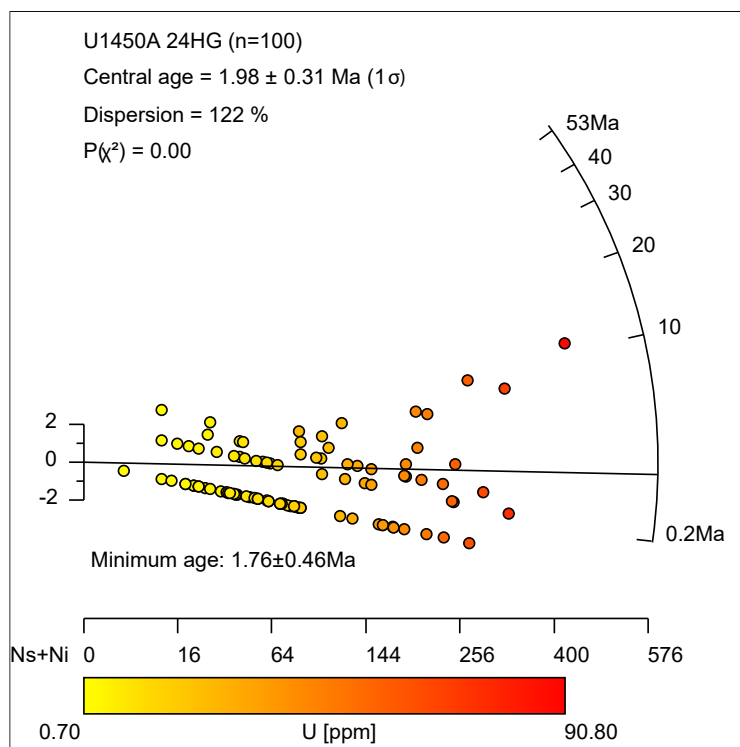
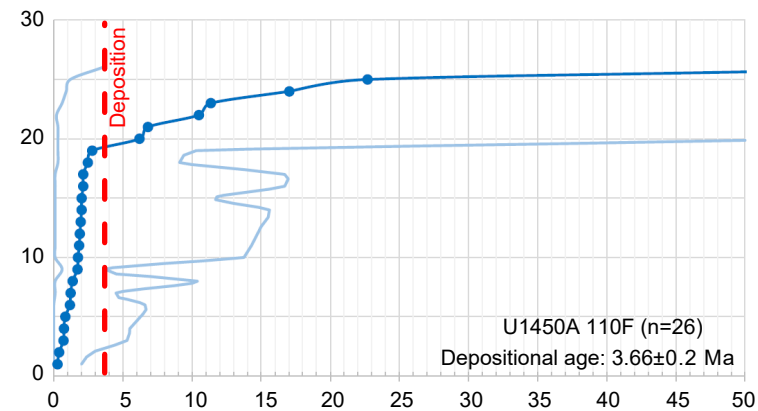
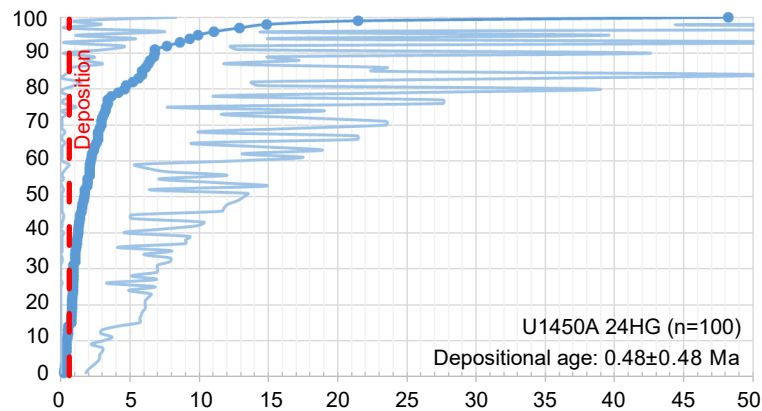
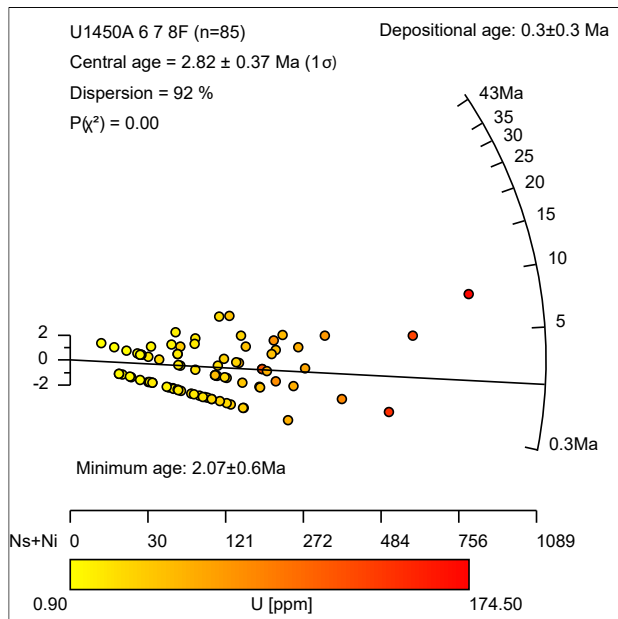
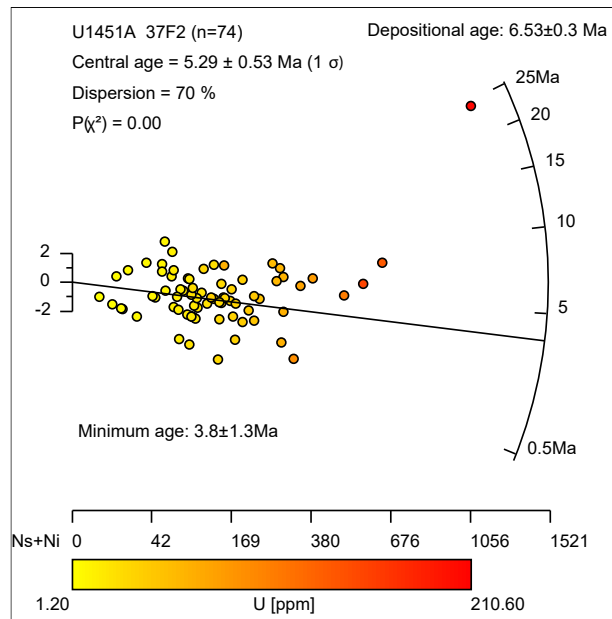


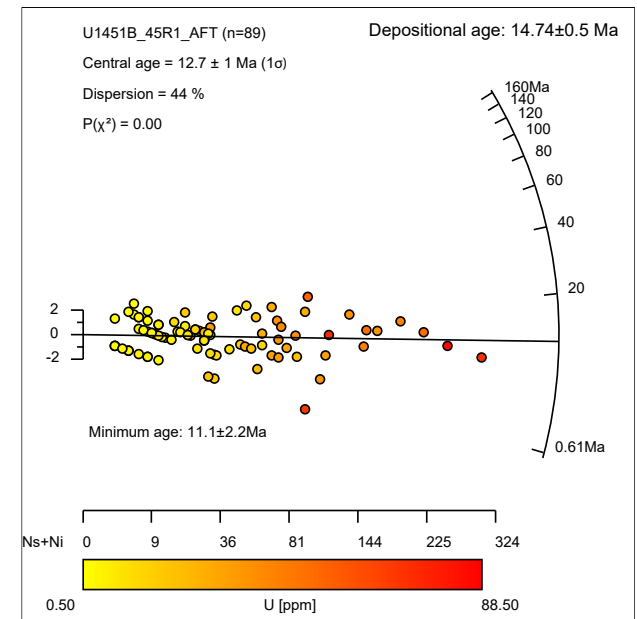
Figure 3



(a)



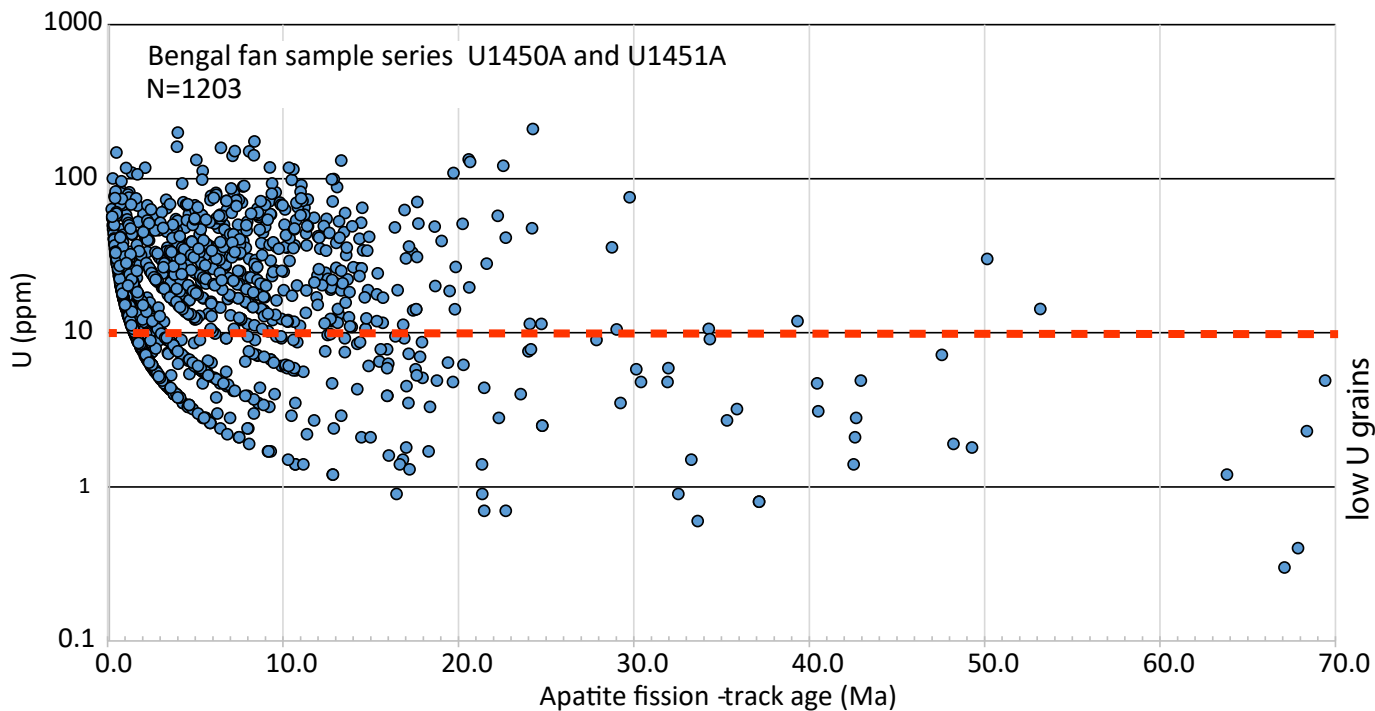
(b)



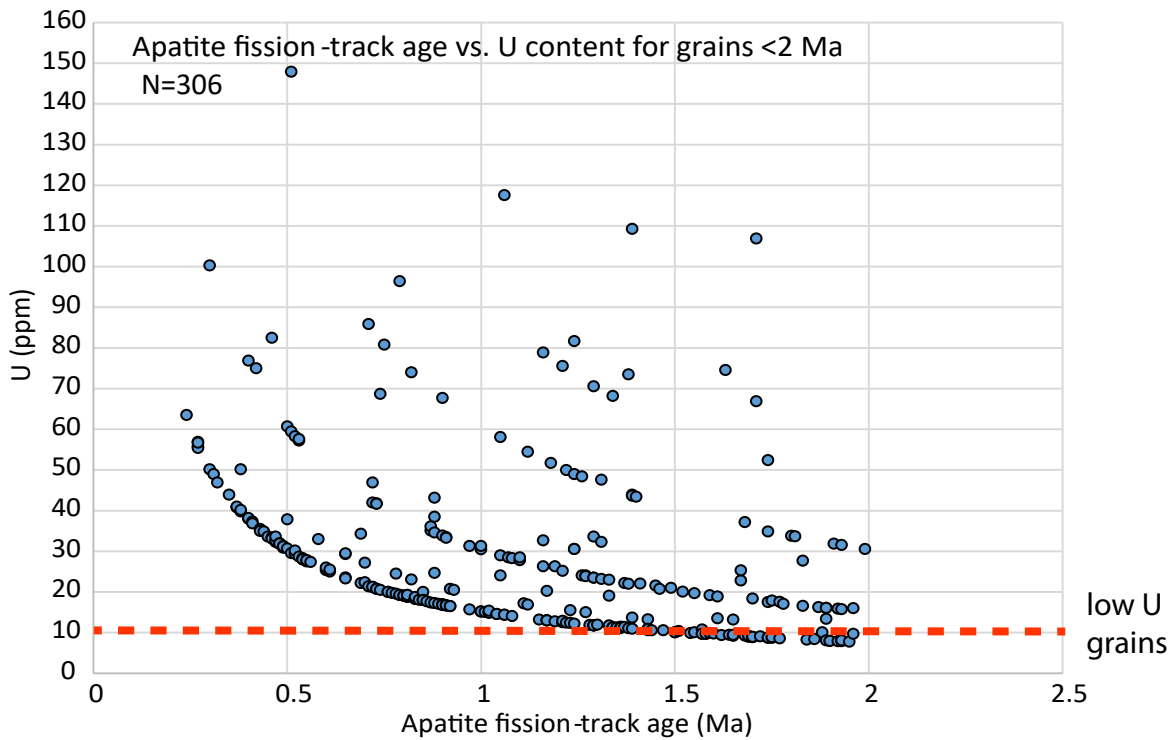
(c)

Figure 4

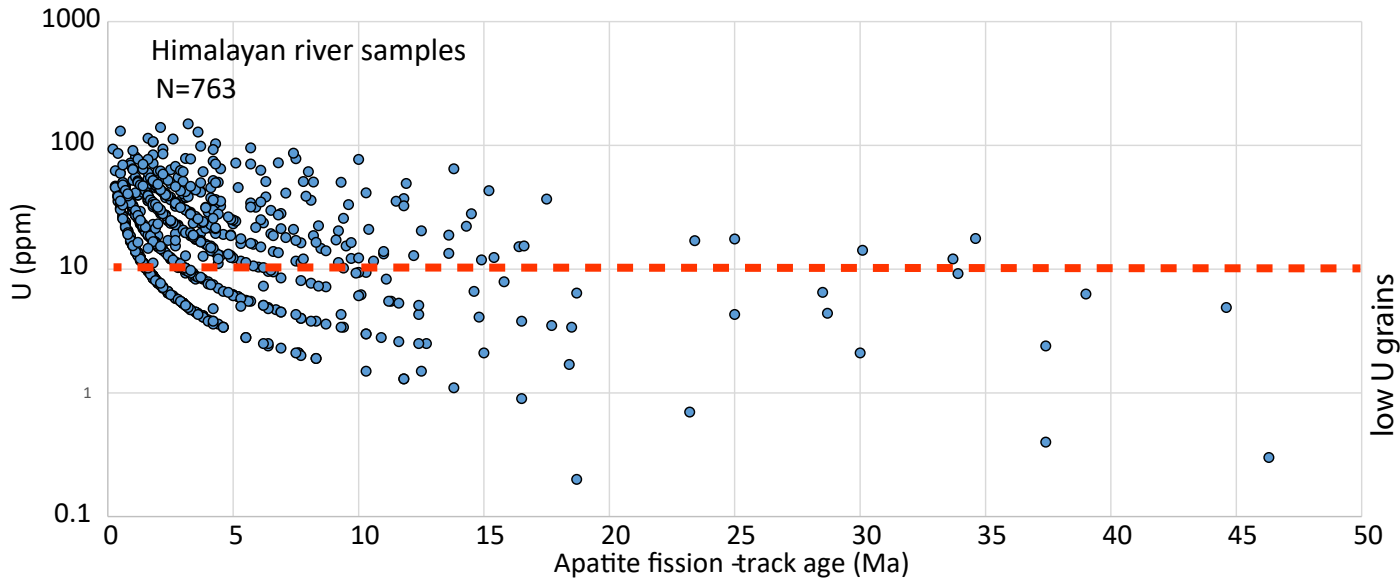
A) Apatite fission-track age vs. U content



B) Apatite fission-track age vs. U content for grains <2 Ma



C) Himalayan river samples



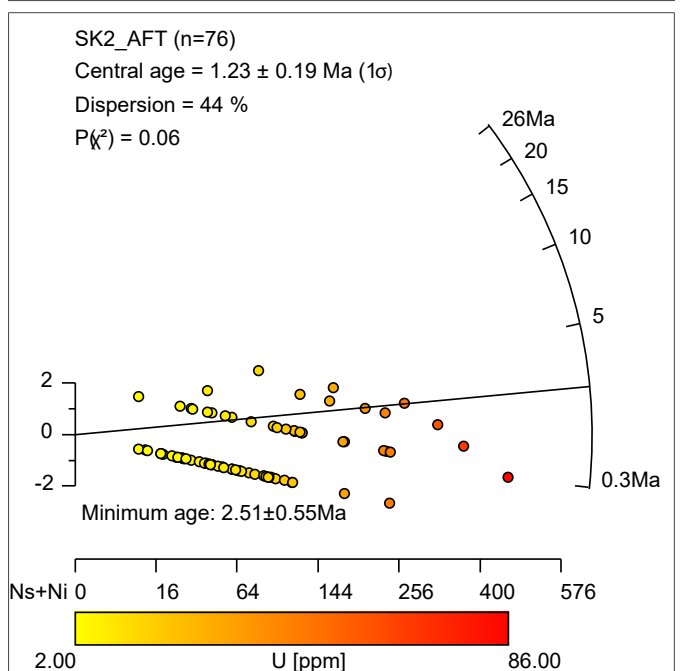
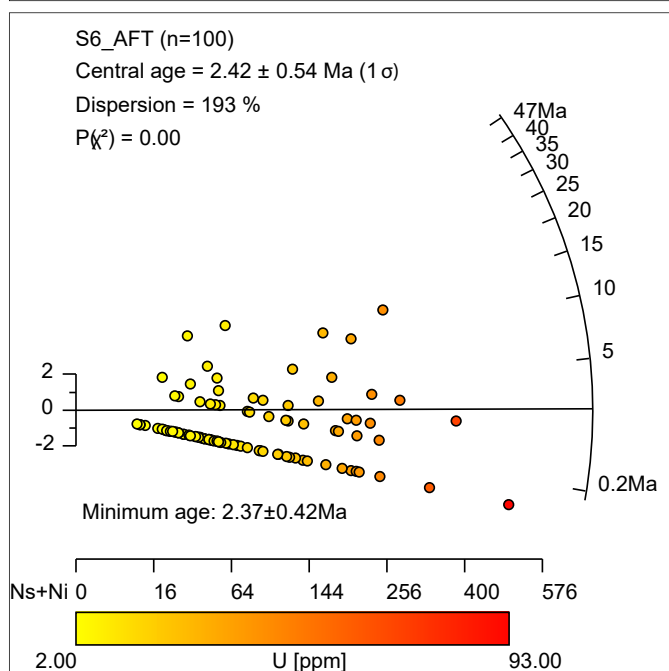
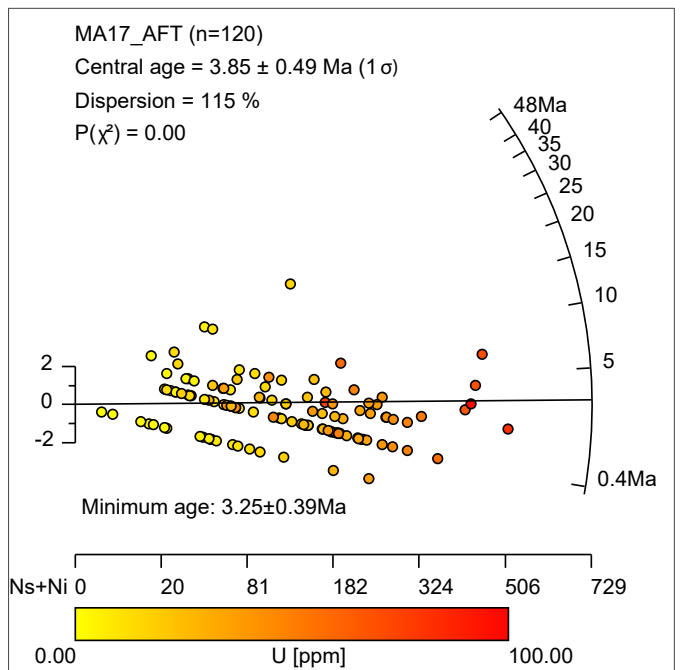
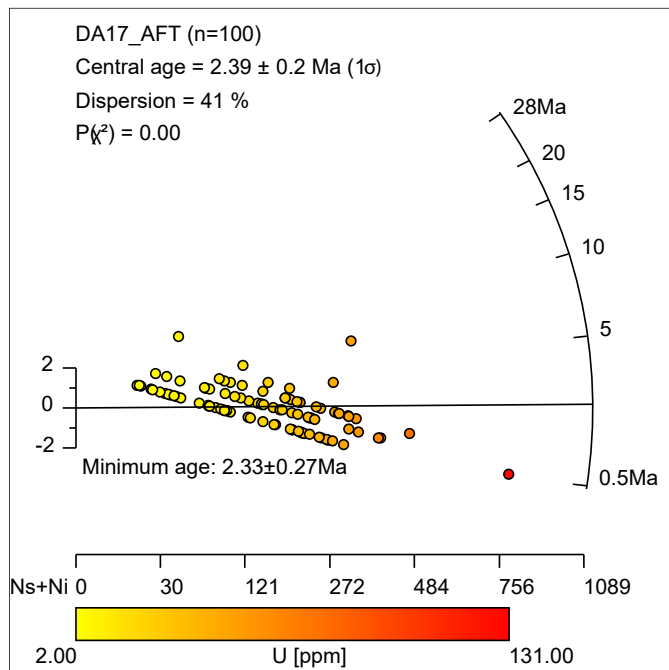
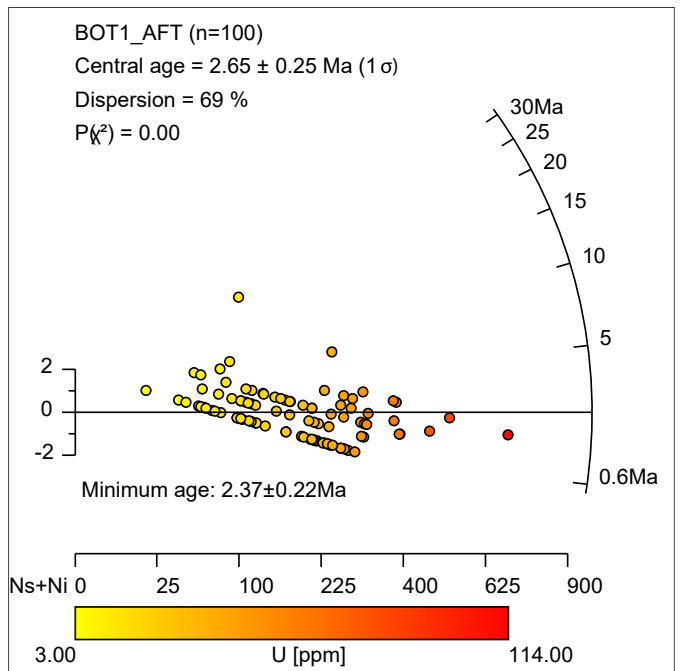
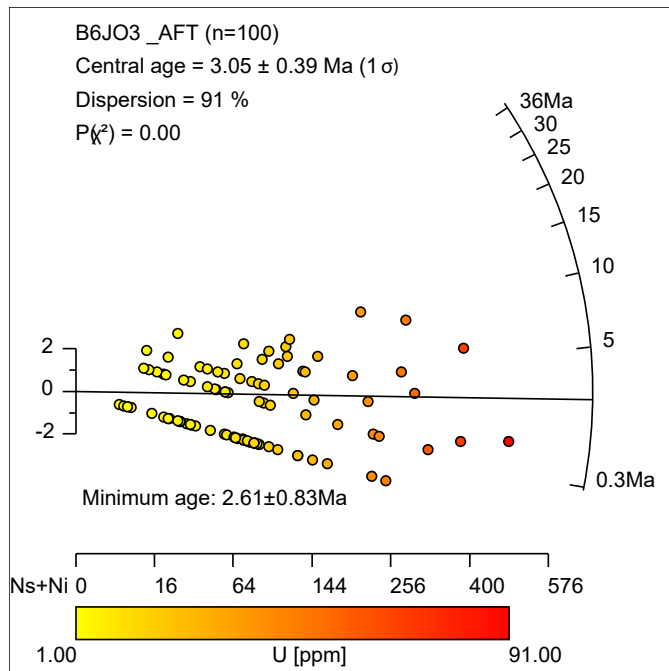


Fig. 6

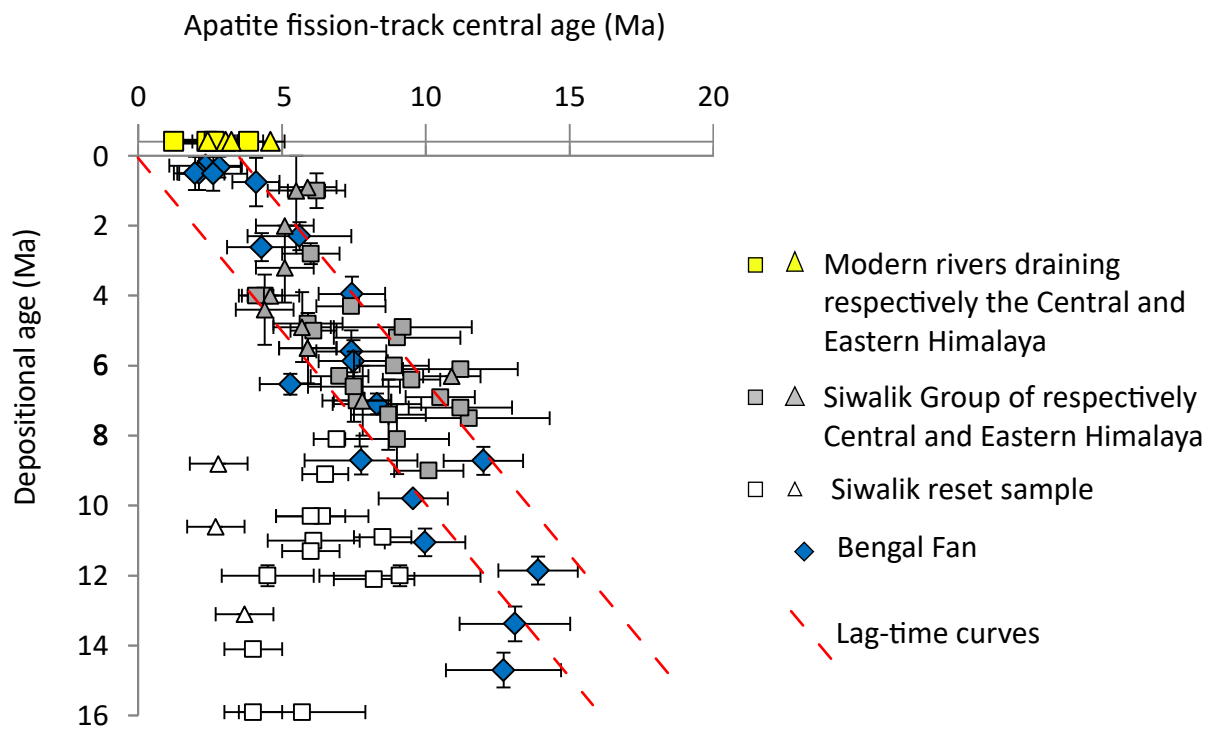
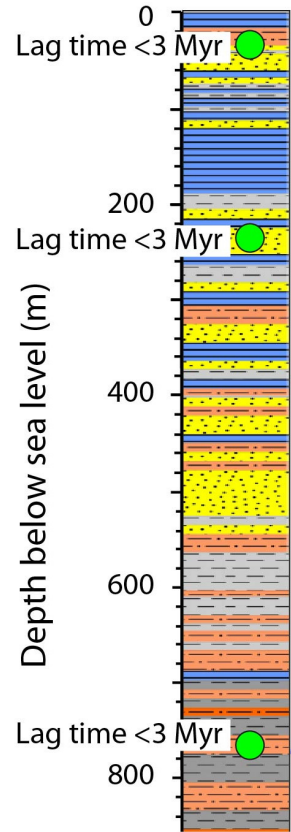


Figure 7

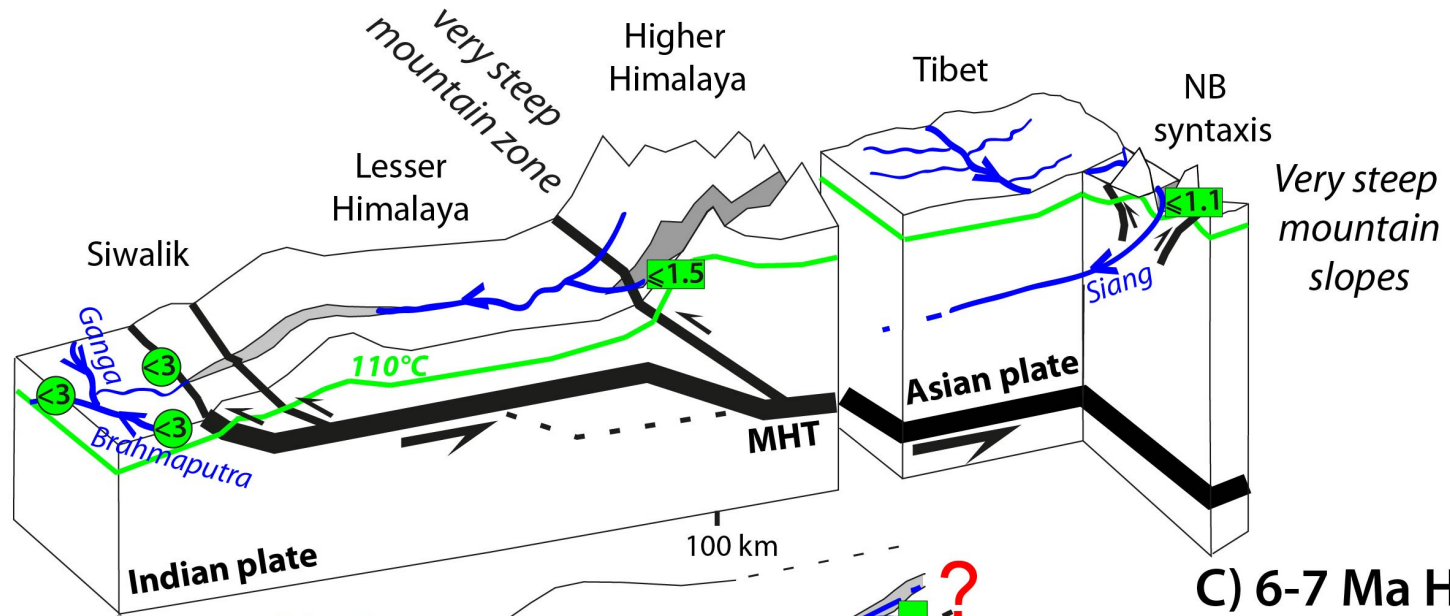


# A) Bengal Fan

## Site U1451



# B) Modern Himalaya



# C) 6-7 Ma Himalaya



# D) 12-13 Ma Himalaya

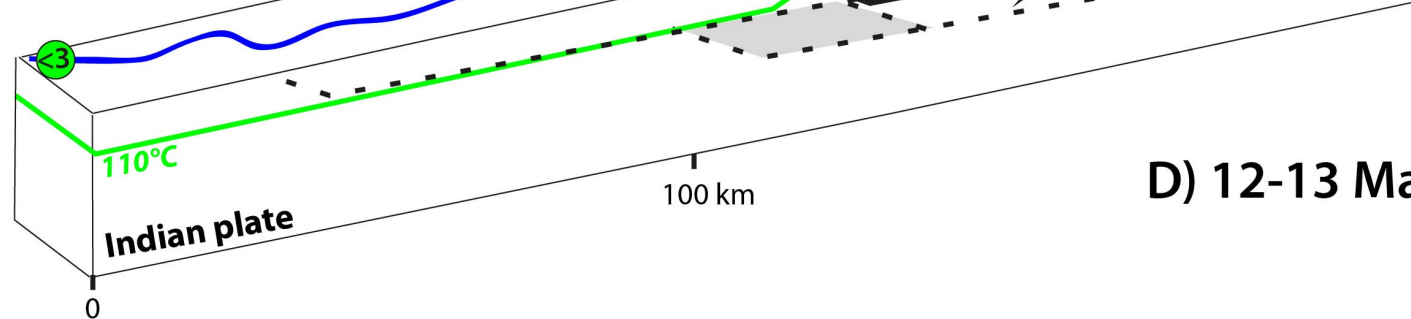


Figure 8