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Where is basalt in river sediments, and why does it matter?

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24 **Abstract**

25 Weathering, erosion and mineralogical sorting processes modify the chemical and isotopic
26 compositions of sediments relative to those of their source rocks. The way and extent to which
27 those processes affect the geochemistry of sediments is however not yet fully understood. Here,
28 we report trace element data as well as Nd, Hf and Pb isotopic compositions of sediments sampled
29 at different water depths in the Ganges, Yamuna and Chambal Rivers draining the Deccan Traps
30 basalts and the crystalline and sedimentary rocks from the Himalayan mountain range and the
31 northern Indian shield.

32 Isotopic differences between surface and bed sediments sampled at the same location reach $6 \epsilon_{Nd}$
33 and about $15 \epsilon_{Hf}$ units, suggesting that suspended loads and bedloads do not carry similar
34 provenance information. Such differences are explained by the combined effects of differential
35 erosion and mineralogical sorting processes during fluvial transport. Materials eroded from basalts
36 are preferentially transported in suspension near the river surface while materials eroded from more
37 crystalline precursors are transported near the bottom of the river. This depth-dependent
38 provenance within the river channel leads to an overrepresentation of basaltic materials in fine-
39 grained suspended loads that are finally delivered into the ocean and become part of the oceanic
40 terrigenous clays. By contrast, the proportion of basaltic materials in coarser sediments such as
41 bedloads or turbidites is underestimated.

42 Our results have important consequences on the use of Nd, Hf and Pb isotopic compositions of
43 sediments as provenance proxies because they indicate that all grain-size fractions must be taken
44 into account to properly trace source compositions. They also suggest that upper continental crust
45 estimates derived from fine-grained sediments, such as suspended loads, may be biased towards
46 basaltic compositions if basaltic outcrops are present in the drainage area.

47 **Keywords :**

48 Neodymium; Hafnium; Lead; Isotopes; River sediments; Himalaya; Deccan Traps

49

50 **1. Introduction**

51 River sediments are essentially mixtures of particles and minerals derived from the erosion of rocks
52 exposed in the catchment area. Their chemical and isotopic compositions are often used to trace
53 sources, estimate the average composition of the drained area or determine chemical and physical
54 erosion rates in large basins (e.g. Goldstein et al., 1984; Goldstein and Jacobsen, 1988; Asmerom
55 and Jacobsen, 1993; Allègre et al., 1996; Galy et al., 2001; Clift et al., 2002; Singh and France-
56 Lanord, 2002; Vance et al., 2003; Millot et al., 2004; Kamber et al., 2005; Richards et al., 2005;
57 Roddaz et al., 2005; Belousova et al., 2006; Singh et al., 2008; Singh, 2009; Dhuime et al., 2011;
58 Padoan et al., 2011; Lupker et al., 2011; 2012a). However, using sediments as such proxies requires
59 a proper understanding of biases introduced by erosion and sedimentary processes on chemical and
60 isotopic compositions. Some studies have previously shown that the geographical extend of the
61 source rocks in the catchment area do not always match with the proportions deduced from the
62 isotopic compositions of sediments (Allègre and Rousseau, 1984; Goldstein and Jacobsen, 1988;
63 Kramers and Tolstikhin, 1997; Tricca et al., 1999; Steinmann and Stille, 2008; Dhuime et al.,
64 2011). This is because some lithologies are more erodible than others and/or are affected differently
65 by climates that favor either chemical or physical alteration of rocks. Besides, it has been shown
66 that the hydrodynamic sorting of particles within the water column during fluvial transport
67 introduces large fractionation of the chemical and isotopic messages carried by bedload and
68 suspended load sediments (Lupker et al., 2011; Bouchez et al., 2011; Garzanti et al., 2010; 2011;
69 Garçon et al., 2013a; 2013b; 2014). Here, we go one step further and evaluate the combined effects
70 of (a) contrasting climate and rock erodibility in the catchment area of a large river system and (b)

71 isotopic fractionation caused by hydrodynamic sorting in the water column during fluvial transport.
72 We discuss trace element concentrations and Nd, Hf, Pb isotopic compositions of sediments
73 sampled at different water depths in the Ganges fluvial system that drains the Deccan Traps basalts
74 and the crystalline and sedimentary rocks of both the Himalayan range and the northern Indian
75 shield. We show that bedloads and suspended loads carry different provenance information and
76 discuss potential implications for worldwide terrigenous sediments.

77 **2. Geological setting and Sampling**

78 Sedimentary material was recovered at three different sampling sites along the Ganges fluvial
79 system (Figure 1). Samples include bedload and suspended load sampled at different water depths
80 in the Yamuna and Ganges Rivers as well as bank sediments and surface suspended loads from the
81 Chambal River. All samples were recovered at high flow during the monsoon season (July to
82 September) from 1996 to 2009. Bank sediments were sampled on the river shore while bedloads
83 were dredged up from the bottom of the rivers. Suspended loads were sampled at the same location
84 than bedloads, at the water surface or at different depths within the river channel. They were
85 recovered after filtration of about 5L of river water under pressure through 0.2 μm filters. Detailed
86 sampling techniques can be found in Galy et al. (2008) and Lupker et al. (2011).

87 The first sampling site is located in Bangladesh at the outflow of the Ganges River (Figure 1);
88 given its location, it integrates all sediments transported by the Ganges and its tributaries. The
89 drainage basin covers about one million km^2 and includes Quaternary fluvial deposits from the
90 Indo-Gangetic floodplain, variably metamorphosed crystalline and sedimentary rocks from both
91 the Himalayan mountain range and the northern Indian shield, and few basaltic rocks from the
92 Deccan Traps (Le Fort, 1975; Krishnan, 1982). At this location, the Deccan Traps basalts represent
93 only 4% of the total drained area. Major and trace element concentrations, as well as Nd, Hf and

94 Pb isotopic compositions of sediments sampled at this location have been previously published by
95 Lupker et al. (2012) and Garçon et al. (2013a; 2013b) but are reported for convenience in Table 1.
96 The two other sampling sites are both located upstream in the floodplain, in the Yamuna and in the
97 Chambal Rivers. At the Yamuna sampling site, the drainage basin consists of ~20% of basalts from
98 the Deccan Traps, ~40% of crystalline and sedimentary rocks from both the Himalayan mountain
99 range and the northern Indian shield and ~40% of Quaternary floodplain deposits, mostly derived
100 from the erosion of the Himalayas (Figure 1). At the Chambal sampling site, the Deccan Traps
101 basalts constitute 30% of the basin area, the crystalline and sedimentary rocks from the Indian
102 shield represent ~60% and the remaining 10% consists of Quaternary floodplain deposits
103 containing the erosion products of both the Deccan Traps basalts and the Indian shield (Figure 1).

104

105 **3. Analytical techniques**

106 All samples were powdered in agate bowls using a planetary ball mill. They were pre-treated for 2
107 days in HNO₃ 14N on a hot plate at 130°C, then evaporated and digested in a HF-HClO₄ mixture in
108 PARR® bombs for 6 weeks at 140°C or one week at 200°C. After complete dissolution, trace
109 element concentrations and Nd-Hf-Pb isotopes were measured following the procedures described
110 by Chauvel et al. (2011). Repeated measurements of BR or BR-24 rock standards were used to
111 calibrate trace element concentrations. The validity and reproducibility of the trace element data is
112 estimated to be better than 5% for most elements based on the analyses of several complete
113 duplicates and repeated measurements of international rock standards as unknown samples,
114 including sedimentary materials such as JSd-2 (see Supplementary Table 1 for more details).
115 Neodymium, Hf, and Pb were isolated using ion chromatography (Chauvel et al., 2011). Total
116 procedural blanks were less than 100 pg for Nd, Hf and Pb. Isotopic compositions were measured

117 on a Nu Plasma HR MC-ICP-MS at the ENS Lyon (France). For Nd and Hf, mass bias corrections
118 were performed using $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$ and $^{179}\text{Hf}/^{177}\text{Hf}=0.7325$, respectively. The reproducibility
119 (2σ) of the Ames-Rennes Nd and Ames-Grenoble Hf reference standards run every two or three
120 samples was better than 40 ppm for $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios. The analytical drift was corrected
121 using the recommended values of 0.511961 for the Ames-Rennes Nd (Chauvel and Blichert-Toft,
122 2001) and 0.282160 for the Ames-Grenoble Hf (Chauvel et al., 2011). For Pb, mass fractionation
123 bias was corrected using a thallium spike (White et al., 2000). The reproducibility of the NBS 981
124 reference standard run every two or three samples was better than 170 ppm for $^{208}\text{Pb}/^{204}\text{Pb}$, 130 ppm
125 for $^{207}\text{Pb}/^{204}\text{Pb}$ and 90 ppm for $^{206}\text{Pb}/^{204}\text{Pb}$ ratios. Analytical drifts were corrected by standard-bracketing
126 using the published values of Galer and Abouchami (1998) for the NBS 981 reference standard.

127 **4. Results**

128 Trace element concentrations and Nd, Hf, and Pb isotopic compositions of sediments from the
129 Yamuna and Chambal Rivers are reported in Table 1 together with the previously published data
130 for the Ganges sediments (Garçon et al., 2013a; 2013b).

131 Figure 2 shows spidergrams normalized to the average upper continental crust composition of
132 Rudnick and Gao (2003) for the Yamuna and Chambal sediments. At a first order, the trace element
133 contents of the sediments resemble those of the upper continental crust. Enrichment factors span a
134 relatively small range of values from 0.3 to 3.8 for all trace elements (Figure 2). No significant
135 trace element variation is noticed between the Chambal and Yamuna sediments but systematic
136 discrepancies are observed between suspended loads and bedloads/bank sediments. Compared to
137 bedloads and bank sediments, suspended loads show generally lower Zr, Hf but higher Cs, Rb, Ba,
138 Pb, Li and transition element (Sc, V, Cr, Co, Ni, Cu, Zn) contents. These chemical differences,
139 similar to those observed in the Ganges bedloads and suspended loads (Garçon et al., 2013a), are

140 well explained by mineral sorting processes that occur during the fluvial transport of sediments.
141 High Zr-Hf concentrations in bedloads and bank sediments result from preferential concentration
142 of zircons at the bottom of the river while high mobile and transition element concentrations in
143 suspended loads are due to higher proportions of phyllosilicates and oxides in suspension within
144 the water column (see Lupker et al., 2011; Garzanti et al., 2010; 2011 and Garçon et al., 2013a for
145 further details). Bank sediment BR 938 from the Chambal River (gray dashed line in Figure 2) does
146 not exhibit the typical trace element features of bedloads/bank sediments. Instead, its trace element
147 pattern strongly resembles that of suspended loads with typical low Zr-Hf contents and high mobile
148 and transition element concentrations. Major element concentrations published by Lupker et al.
149 (2012b) showed that this particular sample is also characterized by a high $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio (i.e. 0.20)
150 compared to values usually found in bedloads and bank sediments (i.e. $\text{Al}_2\text{O}_3/\text{SiO}_2 < 0.16$ according
151 to Garçon et al., 2013a). This strongly suggests that BR 938 contains anomalously high proportions
152 of Al_2O_3 -rich clays and that its composition more likely reflects that of a suspended load. Finally,
153 Figure 2 shows that, compared to the Ganges sediments, suspended loads from the Chambal and
154 Yamuna Rivers generally have lower Zr, Hf, Nb, Ta and Light Rare Earth Element (LREE)
155 contents together with higher transition element contents.

156 Nd and Hf isotopic compositions of the Yamuna and Chambal sediments span large ranges of
157 values ($-16.6 < \epsilon_{\text{Nd}} < -9.9$; $-24.2 < \epsilon_{\text{Hf}} < -4.5$; Table 1) and are generally more radiogenic than the Ganges
158 sediments ($-17.8 < \epsilon_{\text{Nd}} < -16.8$; $-30.2 < \epsilon_{\text{Hf}} < -18.8$; Table 1). At both sampling sites, suspended loads
159 have more radiogenic Nd and Hf isotopic compositions than bedloads and bank sediments,
160 excluding the outlier sample BR 938.

161 Lead isotopic compositions of the Yamuna and Chambal sediments range between 39.00 and 40.50
162 for $^{208}\text{Pb}/^{204}\text{Pb}$, 15.72 and 15.88 for $^{207}\text{Pb}/^{204}\text{Pb}$ and 18.71 and 19.96 for $^{206}\text{Pb}/^{204}\text{Pb}$. Suspended loads tend

163 to be less radiogenic than bedloads and bank sediments and all sediments from the Chambal and
164 Yamuna rivers are generally less radiogenic than those from the Ganges ($39.99 < {}^{208}\text{Pb}/{}^{204}\text{Pb} < 42.45$;
165 $15.87 < {}^{207}\text{Pb}/{}^{204}\text{Pb} < 16.11$; $19.78 < {}^{206}\text{Pb}/{}^{204}\text{Pb} < 22.16$).

166 **5. Discussion**

167 **5.1. Chemical and isotopic variations as a function of water depth**

168
169 **5.1.1. Ganges sediments from the delta**
170
171 Neodymium, Hf and Pb isotopic compositions of sediments sampled at different water depths in
172 the Ganges River in Bangladesh are shown in yellow in Figure 3. The first remarkable feature is
173 that the Nd isotopic compositions of the Ganges sediments do not change with water depth and
174 exhibit a constant value at $\epsilon_{\text{Nd}} \approx -17$. This value is indistinguishable from the average isotopic
175 signature of river sediments sampled at the Himalayan front i.e. sediments draining exclusively the
176 Himalayan mountain range (Garçon et al., 2013a), showing the overwhelming contribution of the
177 crystalline and sedimentary Himalayan sources to the total sedimentary budget of the Ganges in
178 the delta (Galy and France-Lanord, 2001). Using major element ratios, Lupker et al. (2012b)
179 estimated that the contribution of the Deccan Traps basalts at the outflow of the Ganges in
180 Bangladesh can be highly variable from year to year but is less than 4% in the Ganges sediments
181 sampled in 2004, 2007 and 2008 and used in this study. A quick isotopic mass balance calculation
182 between 4% sediment with an $\epsilon_{\text{Nd}} \approx +5$ typical of Deccan Traps basalts and 96% sediment with the
183 low ϵ_{Nd} typical of the Himalayan units ($\epsilon_{\text{Nd}} \approx -17$) shows that the resulting value is indistinguishable
184 from that of the Himalayan sources. Note that the contribution of erosion products from the
185 northern Indian shield cannot be distinguished from that of the Himalayan units because they are
186 isotopically equivalent (Parrish and Hodges, 1996). Similarly, the contributions of the Quaternary
187 floodplain deposits having already reworked the erosion products of the Himalayas cannot be

188 distinguished from the actual contribution of the crystalline and sedimentary rocks from the
189 Himalayan mountain range because they share the same composition.

190 In contrast to Nd, ϵ_{Hf} and Pb isotopic ratios change with water depth in the Ganges profile (Figure
191 3): bottom sediments have lower ϵ_{Hf} and more radiogenic Pb isotopic ratios than the overlying
192 suspended loads. These differences result of a “heavy mineral effect” caused by hydrodynamic
193 sorting processes during sediment transport, with a preferential concentration of coarse and dense
194 minerals at the bottom of the river. Indeed, Garçon et al. (2013a; 2013b; 2014) showed that the
195 excess of zircon, monazite and allanite in both bedloads and bank sediments shifts the Hf and Pb
196 isotopic compositions of these sediments towards low ϵ_{Hf} and high Pb isotope ratios compared to
197 suspended loads.

198

199 **5.1.1. Chambal and Yamuna rivers draining the Deccan Traps**

200 Upstream in the floodplain, sediments from the Yamuna and Chambal Rivers are isotopically very
201 different from the Ganges River samples (Table 1, Figure 3). They have generally higher ϵ_{Nd} and ϵ_{Hf}
202 values and less radiogenic Pb isotopic ratios that can simply be explained by a higher contribution
203 of basaltic erosion products from the Indian Deccan Traps (Figure 3). The isotopic variations as a
204 function of water depth are however more surprising. First, excluding the outlier bank sediment
205 BR 938 that contains suspended load-type material (see section 4), the ϵ_{Nd} of the Yamuna and
206 Chambal sediments dramatically decrease with depth, from -10 at the surface to about -16 at the
207 bottom of the river, a feature unknown in the Ganges sediments. Second, the downward decrease
208 of ϵ_{Hf} and increase of Pb isotopic ratios are much larger than those observed for the Ganges
209 sediments. Differences between surface and bottom sediments in the Yamuna River reach almost
210 15 ϵ_{Hf} units (Figure 3) and cannot result from hydrodynamic processes alone, as it is the case in the

211 Ganges sediments (Garçon et al., 2013a). Indeed, explaining the very radiogenic ϵ_{Hf} of the Yamuna
212 and Chambal surface suspended loads by hydrodynamic sorting only would require these
213 sediments to be almost exclusively made of radiogenic Himalayan minerals such as epidote ($\epsilon_{\text{Hf}} =$
214 $+0.6$, Garçon et al., 2014), garnet ($\epsilon_{\text{Hf}} = -3.1$, Garçon et al., 2014) and magnetite ($\epsilon_{\text{Hf}} = -6.5$, Garçon
215 et al., 2014), a requirement that is not supported by petrological observations under the binocular
216 microscope. Instead, such isotopic variations with depth suggest, together with the Nd isotopic
217 change, that surface suspended loads from both the Yamuna and Chambal Rivers include much
218 higher proportions of basaltic erosion products from the Deccan Traps than the bed sediments,
219 which are dominated by erosion products from the crystalline and sedimentary rocks of the
220 Himalayan range and the Indian shield (Figure 3).

221 This interpretation is further supported by the trace element concentrations of the sediments (Figure
222 2). Suspended loads from the Chambal and Yamuna Rivers are significantly enriched in transition
223 elements (i.e. Sc, V, Cr, Co, Ni, Cu, Zn) and depleted in incompatible elements (i.e. Zr, Hf, Nb, Ta
224 and LREE) compared to both the Ganges sediments and the bedloads/bank sediments from the
225 same rivers (Figure 2). These features are typical of the trace element signature of basalts and are
226 therefore consistent with the presence of higher amount of Deccan Traps material in the suspended
227 loads of the Yamuna and Chambal Rivers. Furthermore, Figure 4 illustrates the variations of two
228 trace element ratios (La/Sm and Ni/Hf) as a function of depth in the Yamuna, Chambal and Ganges
229 Rivers. La/Sm and Ni/Hf ratios of sediments can be used to distinguish crustal from basaltic sources
230 because magmatic processes significantly fractionate these two ratios: the Himalayan and Indian
231 crystalline and sedimentary rocks are typically characterized by high La/Sm and low Ni/Hf while
232 the Deccan Traps basalts exhibit low La/Sm and high Ni/Hf (see the green and red fields in Figure
233 4). The downward variations seen in Figure 4 of both La/Sm and Ni/Hf ratios in the Chambal and

234 Yamuna depth profiles are consistent with a decreasing proportion of basaltic erosion products
235 from the water surface to the bottom of the rivers.

236 Both isotopes and trace element data thus support the idea that bedloads and suspended loads from
237 the Yamuna and Chambal Rivers do not share similar provenance information. This can be
238 explained by the contrasting erosion style of the Deccan Traps basalts, subjected to higher chemical
239 erosion in the plain, versus the crystalline and sedimentary rocks from the Himalayas subjected to
240 higher physical erosion at high altitude. Indeed, previous studies suggest that the Deccan Traps
241 basalts are chemically more altered than the surrounding crystalline and sedimentary rocks (Dessert
242 et al., 2001; Das et al., 2005; Rengarajan et al., 2009). This leads to the formation of basaltic erosion
243 products enriched in montmorillonite, a fine and flaky clay mineral that tends to remain in
244 suspension in the water column (Jha et al., 1993). Derry and France-Lanord (1996), Singh et al.
245 (2008) and Lupker et al. (2012b) thus suggest that basaltic erosion products from the Deccan Traps
246 might be found in higher proportion in fine-grained sediments in the Ganges and the Bengal fan.
247 Our data further support these suggestions, showing that the erosion products of the more
248 weatherable basalts are likely finer and preferentially transported in suspension near the river
249 surface whereas the erosion products of the more resistant crystalline and sedimentary rocks are
250 coarser and preferentially transported near the bottom of the river.

251

252 **5.2. Quantification of basaltic vs. crystalline material in the sediments**

253
254 Using the relationship between Nd and Hf isotopes as shown in Figure 5, we estimated the
255 proportion of basaltic erosion products at different water depths in the Yamuna and Chambal
256 sediments. As the Hf isotopic signature of the Deccan Traps basalts is poorly documented and no
257 Nd-Hf data have been reported in the literature for the area drained by the Chambal River (Figure

258 1); we performed our mixing calculations using two extreme values for the Deccan Traps
259 endmember (see Figure 5a-b, and Supplementary Table 2 for more details). Both calculations give
260 nevertheless similar results. Figure 5 shows that the Nd and Hf isotopic compositions of the
261 Yamuna and Chambal sediments can be reproduced through mixing between radiogenic material
262 eroded from the Deccan Traps (red squares in Figure 5) and sedimentary material sampled at
263 different water depths in the Ganges River i.e. sediments that represent the erosion products of the
264 Himalayan range and the northern Indian shield (yellow points in Figure 5). The surface suspended
265 loads from both Yamuna and Chambal Rivers have the highest ϵ_{Nd} and ϵ_{Hf} values and are well
266 explained by a contribution of 30-60% of Deccan Traps basalts associated to 40-70% of Ganges
267 surface suspended loads, depending on which endmember is used for the Deccan Traps basalts (cf.
268 Figure 5a-b). The slightly lower ϵ_{Nd} and ϵ_{Hf} values of deeper suspended loads require 20 to 50% of
269 basaltic material. Finally, the bedloads and bank sediments from Yamuna and Chambal rivers
270 resemble those of the Ganges River and include only 10-20% of Deccan Traps basalts. Our
271 calculations thus quantitatively show that the proportion of basaltic erosion products decreases with
272 depth in both rivers, demonstrating that bedloads and suspended loads sampled at the same location
273 can record different provenances. To our knowledge, no publication reports similar data although
274 Bouchez et al. (2011) mentioned the existence of a “provenance stratification” in the Amazon river
275 based on Sr isotopic compositions of sediments.

276 Variations of Pb isotopic ratios in the Ganges, Yamuna and Chambal sediments are generally in
277 agreement with Nd and Hf isotopic compositions even if things are slightly more ambiguous
278 (Figure 3; Figure 6). The Deccan Traps basalts have relatively low $^{206-207-208}Pb/^{204}Pb$ while sediments
279 from the Himalayan Range have generally higher but mainly more variable Pb isotopes. Here again,
280 the Yamuna and Chambal sediments have generally less radiogenic signatures than the Ganges

281 River sediments, a feature consistent with a higher involvement of material deriving from the
282 Deccan Traps basalts. However, the influence of the different sources on Pb isotopic ratios is
283 blurred by the effect of hydrodynamic sorting that concentrates heavy minerals, such as zircon,
284 monazite and allanite, with extremely radiogenic Pb isotopic ratios in the coarse sediments while
285 fine-grained sediments, poorer in heavy minerals, have less radiogenic values (Garçon et al., 2013b,
286 2014). In addition, the large range of Pb isotopic compositions reported for the Deccan Traps
287 basalts makes it impossible to calculate quantitative proportions of basaltic materials in the
288 Yamuna and Chambal sediments (Figure 6).

289

290 **5.3. Bias potentially introduced for provenance studies and crustal estimates**

291

292 The extent of the provenance bias generated by erosion and sedimentary processes can be estimated
293 by comparing the proportion of basalt exposed in the catchment areas of the Yamuna and Chambal
294 Rivers to the proportion of basaltic material effectively present in the river sediments i.e. the
295 proportion estimated above using Nd and Hf isotopic compositions. The Nd and Hf isotopic
296 compositions of the Chambal bank sediment suggest that this sediment almost exclusively derives
297 from the erosion of the Indian shield (Figure 5) and mixing calculations indicate that it includes
298 less than 10% of basaltic material. In contrast, the Deccan Traps basalts represent about 30% of
299 the drainage area at this sampling location (Figure 1). Similarly, the Deccan Traps basalts cover
300 about 20% of the drained area at our Yamuna River site but our calculation indicates that the
301 proportion of basaltic material in the bottom sediments is less than 20% (Figure 5). In both rivers,
302 basaltic material is underrepresented in coarse-grained sediments. In contrast, surface suspended
303 loads consist of 30-60% of material eroded from the Deccan Traps basalts for the Yamuna River
304 and the Chambal River; hence basaltic material is overrepresented in fine suspended loads. Such

305 an isotopic bias has wider implications because it certainly also affects oceanic detrital sediments.
306 Indeed, if as demonstrated here, eroded basalts are overrepresented in surface suspended loads
307 delivered into the ocean at the mouths of large rivers, then, the contribution of basaltic material in
308 oceanic terrigenous clays could be much higher than the proportion of basalts exposed to
309 weathering on continents. Conversely, the basaltic precursor could be significantly underestimated
310 in coarse terrigenous sediments such as turbidites deposited next to continental margins. The
311 relative mass fluxes between fine-grained suspended load and coarse-grained bedload is not
312 precisely known in the Chambal and Yamuna rivers but Jha et al. (1988) and Bawa et al. (2014)
313 estimate that the suspended sediment flux at the outflow of the Yamuna River vary between 10 and
314 100 million tons per year depending on the sampling year, an amount that is not negligible when
315 compared to the average total sediment flux of 400 million tons/year estimated by Lupker et al.
316 (2011) at the outflow of the Ganges in Bangladesh. Furthermore, Lupker et al. (2012b) shows that
317 the contribution of the Deccan Traps basalts in the Ganges sediments in Bangladesh is also highly
318 variable from year to year, ca. 4% in 2007 and 2008 but up to 17% in 2005. This demonstrates that
319 the flux of basalt-dominated suspended sediments can represent a non-negligible part of the total
320 sediment flux that is discharged in the Bay of Bengal for certain years.

321 The overrepresentation of volcanic sources in oceanic sediments was highlighted 25 years ago by
322 McLennan et al. (1989) and more recent work showed the preponderant role of chemical
323 weathering of basalts on the composition of the seawater (Dessert et al., 2001; 2003). What our
324 new results demonstrate is that rock erodibility, climate and river hydrodynamics affect the Nd, Hf
325 and Pb isotopic compositions of detrital sediments to an extent that was not previously imagined.
326 Our data suggests that the overestimation of basaltic material in fine-grained sediments could reach
327 at least a factor of 2 (Figure 5). We acknowledge that, at the global scale, basalt exposures cover

328 only about 5% of the total continental surfaces (Amiotte Suchet et al., 2003), which may not be
329 enough to bias the overall isotopic composition of oceanic and continental sediments. We however
330 expect this effect to be significant for detrital sediments deposited next to subduction zones and
331 orogenic areas such as the Andes or the Cascades mountain ranges where significant amount of
332 basalts are exposed to weathering. The over/under-representation of basaltic erosion products
333 certainly also affect detrital materials discharged by several large river systems such as the Nile
334 River in Africa or the Parana River in South America where basalts cover respectively 20% and
335 12% of the total drainage area (Amiotte Suchet et al., 2003). All grain-size fractions, but not only
336 fine-grained sediments, should thus be considered in studies using Nd, Hf or Pb isotopic data to
337 trace the provenance of detrital sediments and their variations through time (e.g. Hemming and
338 McLennan, 2001; Li et al., 2003; Prytulak et al., 2006; Carpentier et al., 2008; Singh et al., 2008;
339 Carpentier et al., 2014). Our results also indicate that caution should be taken when using
340 sedimentary material as proxies to estimate the average isotopic compositions or ages of large
341 continental areas (e.g. Goldstein et al., 1984; Goldstein and Jacobsen, 1988; Asmerom and
342 Jacobsen, 1993; Plank and Langmuir, 1998; Millot et al, 2004; Garçon et al., 2011; Vervoort et al.,
343 2011; Chauvel et al., 2014) because the under/overrepresentation of volcanogenic sources could
344 significantly bias the derived average value depending on the type of sediment that is considered.

345

346 **6. Conclusions**

347 The data reported here reveal that bedload and suspended load sediments do not carry similar
348 provenance information when both basalts and crystalline rocks are exposed in the catchment area.
349 Large Nd, Hf and Pb isotopic differences exist between bedloads/bank sediments and suspended
350 loads sampled at different water depths in the Chambal and Yamuna Rivers draining basaltic,

351 crystalline and sedimentary rocks. In these rivers, basalt-derived materials are overrepresented in
352 fine-grained sediments transported in suspension near the water surface while materials eroded
353 from crystalline and sedimentary rocks are overrepresented in bedload/bank sediments. Mixing
354 models suggest that the bias could be as large as a factor of 2. As river suspended load is a major
355 contributor to the deep oceanic sedimentation, we suggest that basaltic materials may be also over-
356 represented in fine-grained oceanic sediments and under-represented in coarse-grained turbidites.
357 Finally, we emphasize the need to a careful evaluation of the Nd, Hf and Pb isotopic compositions
358 of sediments when used as provenance proxies in both continental and oceanic environments.

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578 **Tables**

579

580 **Table 1:** Trace element concentrations and Nd-Hf-Pb of the Chambal, Yamuna and Ganges
581 sediments

582 * *Data already published by Garçon et al. (2013a ; 2013b)*

583 Uncertainties ($\pm 2\sigma$) reported in the Table for isotopic data correspond to in-run errors. ϵ_{Nd} and ϵ_{Hf}

584 were calculated using the CHUR composition of Bouvier et al. (2008).

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587

Table 1

Sample Name	Depth profile								
	BR 935	BR 937	BR 938	BR 913	BR 912	BR 911	BR 914	BR 717*	BR 415*
Sampling date	14-Aug-09	14-Aug-09	14-Aug-09	9-Aug-09	9-Aug-09	9-Aug-09	9-Aug-09	17-Aug-07	13-Jul-04
Latitude (°N)	26.657	26.657	26.657	26.1306	26.1306	26.1306	26.1306	24.0529	24.0529
Longitude (°E)	77.903	77.903	77.903	79.7539	79.7539	79.7539	79.7539	89.0247	89.0247
River	Chambal	Chambal	Chambal	Yamuna	Yamuna	Yamuna	Yamuna	Ganges	Ganges
Type of sediment	Suspended load	Bank sediment	Bank sediment	Suspended load	Suspended load	Suspended load	Bedload	Bedload	Suspended Load
Sampling depth (m)	0			0.2	3.3	7.3	≈10	11	0
Cs	7.84	1.30	5.02	7.99	7.65	6.15	2.22	3.87	15.4
Rb	105	44.2	77.2	110	109	95.0	57.8	50.3	202
Ba	346	267	325	394	389	362	293	244	627
Th	12.0	15.8	9.50	11.6	12.8	13.5	20.1	74.2	20.0
U	1.95	2.29	1.69	2.73	2.23	2.62	3.69	11.7	4.64
Nb	13.6	8.24	10.5	14.1	14.2	14.9	14.6	20.3	17.4
Ta	1.00	0.655	0.783	1.05	1.08	1.15	1.35	2.50	1.54
La	28.7	34.0	24.2	27.5	30.5	35.8	51.1	141	42.0
Ce	62.6	68.7	54.1	61.0	69.2	78.5	107	292	89.4
Pr	6.95	8.06	6.03	6.66	7.52	8.64	11.8	33.1	9.75
Pb	23.1	14.0	17.5	24.9	28.0	21.3	16.6	14.2	30.4
Nd	27.2	30.2	23.2	25.3	28.6	32.2	43.1	121	35.0
Sr	204	132	180	193	172	167	160	98.3	84.1
Sm	5.57	5.69	4.65	5.20	5.71	6.50	8.24	22.3	6.93
Zr	133	383	159	144	177	276	621	1550	178
Hf	3.53	9.74	4.10	3.75	4.43	6.95	15.3	40.5	4.73
Ti	5415	3588	4334	5038	5118	5216	5019	5299	4137
Eu	1.23	0.902	1.08	1.16	1.18	1.26	1.29	2.24	1.27
Gd	4.86	4.63	4.39	4.76	5.18	5.53	6.61	17.7	6.19
Tb	0.751	0.69	0.664	0.754	0.78	0.839	1.01	2.52	0.984
Dy	4.74	4.24	4.12	4.52	4.75	5.03	5.96	14.7	5.97
Ho	0.935	0.814	0.809	0.898	0.911	0.999	1.14	2.83	1.17
Y	25.9	23.8	23.3	24.9	25.5	28.0	33.7	85.6	32.7
Er	2.62	2.34	2.33	2.59	2.59	2.82	3.40	8.11	3.33
Li	48.5	9.60	30.2	46.6	43.9	35.5	13.4	15.7	51.8
Yb	2.44	2.28	2.17	2.44	2.44	2.79	3.36	8.17	3.18
Lu	0.358	0.344	0.316	0.354	0.356	0.400	0.506	1.25	0.461
Sc	22.0	7.01	12.3	20.4	18.8	16.9	10.7	14.3	15.0
V	162	60.8	115	142	138	120	64.1	53.5	93.4
Cr	123	72.2	83.1	113	108	112	88.5	44.1	76.6
Co	25.7	6.00	18.1	22.5	20.6	17.1	6.82	6.40	15.5
Ni	83.5	19.5	52.3	74.1	67.4	53.1	19.1	12.4	38.6
Cu	106	20.5	54.8	98.2	73.0	47.0	16.9	7.10	33.9
Zn	125	23.5	57.2	157	187	73.9	34.2	31.0	84.9
¹⁴³ Nd/ ¹⁴⁴ Nd ± 2σ	0.512122 ± 8	0.511779 ± 8	0.512038 ± 6	0.512101 ± 8	0.512051 ± 7	0.512008 ± 6	0.511835 ± 5	0.511769 ± 7	0.511752 ± 6
ε _{Nd}	-9.9	-16.6	-11.6	-10.3	-11.3	-12.1	-15.5	-16.8	-17.1
Duplicate									
¹⁷⁶ Hf/ ¹⁷⁷ Hf ± 2σ	0.282656 ± 7	0.282101 ± 7	0.282426 ± 9	0.282605 ± 7	0.282506 ± 5	0.282340 ± 6	0.282140 ± 9	0.281930 ± 6	0.282241 ± 9
ε _{Hf}	-4.5	-24.2	-12.7	-6.4	-9.9	-15.7	-22.8	-30.2	-19.2
Re-run		0.282112 ± 9							
Duplicate							0.282139 ± 9		
²⁰⁶ Pb/ ²⁰⁴ Pb ± 2σ	39.0273 ± 42	40.4987 ± 36	39.2603 ± 38	39.2302 ± 74	39.0014 ± 28	39.6362 ± 24	40.3682 ± 40	42.4525 ± 26	40.3003 ± 18
Re-run			39.2661 ± 26						
²⁰⁷ Pb/ ²⁰⁴ Pb ± 2σ	15.7228 ± 12	15.8277 ± 14	15.7527 ± 12	15.7618 ± 24	15.7500 ± 8	15.8067 ± 8	15.8824 ± 12	16.1109 ± 8	15.8991 ± 6
Re-run			15.7536 ± 8						
²⁰⁸ Pb/ ²⁰⁴ Pb ± 2σ	18.7124 ± 12	19.2689 ± 10	18.8164 ± 12	18.9519 ± 22	18.7890 ± 8	19.2948 ± 8	19.9554 ± 10	22.1618 ± 10	20.0301 ± 6
Re-run			18.8193 ± 8						

Table 1

Sample Name	Depth profile						
	BR 414*	BR 413*	BR 412*	BR 411*	BR 418*	BGP 6*	BR 8253*
Sampling date	13-Jul-04	13-Jul-04	13-Jul-04	13-Jul-04	13-Jul-04	2-Aug-96	10-Sep-08
Latitude (°N)	24.0529	24.0529	24.0529	24.0529	24.0529	24.3583	24.0529
Longitude (°E)	89.0247	89.0247	89.0247	89.0247	89.0247	88.6083	89.0247
River	Ganges	Ganges	Ganges	Ganges	Ganges	Ganges	Ganges
Type of sediment	Suspended Load	Suspended Load	Suspended Load	Suspended Load	Bedload	Bank sediment	Suspended Load
Sampling depth (m)	2	4	6.5	9	10		0
Cs	13.6	11.8	11.7	8.08	2.64	3.83	8.92
Rb	186	174	175	107	56.6	77.9	51.7
Ba	562	531	527	372	212	294	240
Th	19.0	19.3	18.0	15.1	29.7	30.2	16.1
U	4.08	4.15	3.96	2.92	5.14	5.41	1.85
Nb	17.9	16.5	15.7	13.6	18.4	12.9	15.8
Ta	1.57	1.45	1.39	1.37	2.08	1.78	1.31
La	41.3	42.2	40	32.8	71.0	67.1	30.8
Ce	88.1	89.2	84.7	76.3	146	144	75.4
Pr	9.77	9.87	9.29	7.84	16.7	15.5	8.12
Pb	26.2	25.3	25.3	17.4	15.0	17.8	10.5
Nd	35.7	35.8	34.0	29.0	60.4	56.5	31.2
Sr	91.0	99.3	101	88.6	103	115	56.5
Sm	6.98	7.01	6.77	5.60	12.0	10.9	6.27
Zr	204	227	199	249	479	683	196
Hf	5.22	5.79	5.17	6.14	12.1	17.1	5.13
Ti	4198	3976	3833	3314	4355	3155	4323
Eu	1.26	1.23	1.20	1.04	1.48	1.39	1.19
Gd	6.15	6.05	5.80	4.96	10.1	8.51	5.44
Tb	0.945	0.93	0.872	0.782	1.64	1.25	0.854
Dy	5.74	5.72	5.42	4.81	10.3	7.24	5.32
Ho	1.15	1.13	1.06	0.95	2.12	1.39	1.06
Y	32.8	32.5	30.9	27.1	62.0	41.1	31.1
Er	3.3	3.21	3.07	2.65	6.35	3.99	3.04
Li	48.2	43.5	41.9	32.2	15.8	14.7	45.3
Yb	3.11	3.06	2.88	2.51	6.23	3.87	2.95
Lu	0.45	0.448	0.417	0.366	0.905	0.587	0.433
Sc	14.4	13.5	12.8	9.04	13.2	7.74	11.8
V	90.7	81.1	79.1	61.8	46.9	32.7	100
Cr	81.9	67.0	63.4	53.4	40	36.9	73.6
Co	15.1	13.6	13.4	10.3	5.58	3.93	13.8
Ni	40.5	32.4	31.5	26.4	11.7	11.0	39.4
Cu	31.7	25.7	23.7	24.3	10.0	10.9	39.4
Zn	83.5	73.3	72.1	56.6	38.8	29.1	70.4
¹⁴³ Nd/ ¹⁴⁴ Nd ± 2σ	0.511736 ± 8	0.511748 ± 6	0.511745 ± 7	0.511755 ± 6	0.511719 ± 5	0.511758 ± 9	0.511767 ± 8
ε _{Nd}	-17.4	-17.2	-17.3	-17.1	-17.8	-17.0	-16.8
Duplicate				0.511723 ± 7			
¹⁷⁶ Hf/ ¹⁷⁷ Hf ± 2σ	0.282226 ± 6	0.282205 ± 6	0.282209 ± 6	0.282133 ± 7	0.281992 ± 11	0.282027 ± 11	0.282268 ± 7
ε _{Hf}	-19.8	-20.5	-20.4	-23.0	-28.1	-26.8	-18.3
Re-run							
Duplicate							
²⁰⁶ Pb/ ²⁰⁴ Pb ± 2σ	40.3019 ± 24	40.2931 ± 34	40.2725 ± 16	40.1312 ± 28	40.8292 ± 24	40.6213 ± 44	39.9963 ± 28
Re-run							
²⁰⁷ Pb/ ²⁰⁴ Pb ± 2σ	15.9013 ± 6	15.9040 ± 8	15.9040 ± 6	15.8984 ± 10	15.9684 ± 8	15.9733 ± 14	15.8730 ± 14
Re-run							
²⁰⁸ Pb/ ²⁰⁴ Pb ± 2σ	20.0574 ± 8	20.0912 ± 8	20.0756 ± 8	20.0387 ± 10	20.6767 ± 10	20.7277 ± 14	19.7765 ± 10
Re-run							

588 **Figures**

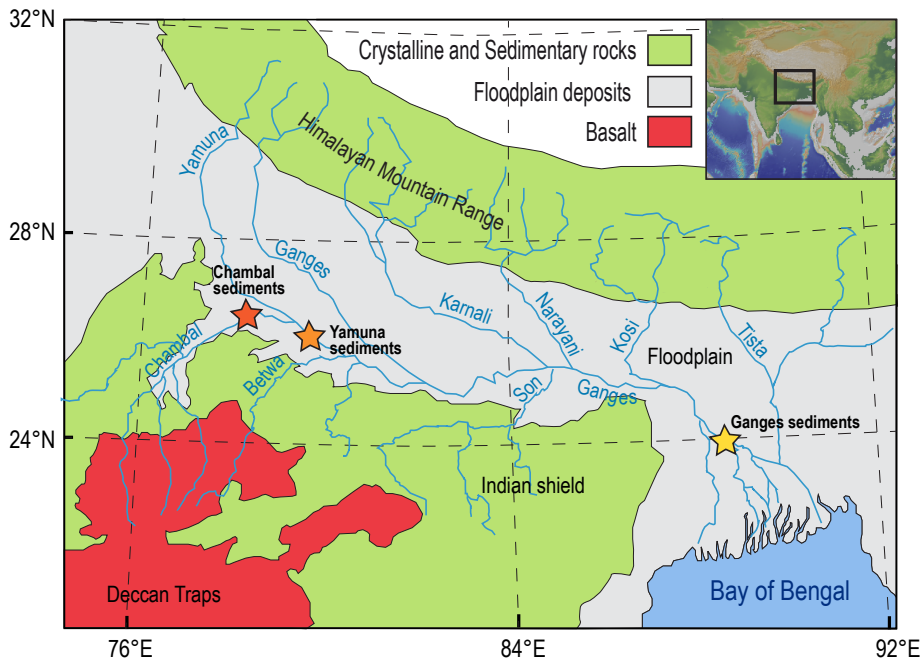
589 **Figure 1:** Map of the Ganges fluvial system showing where crystalline, sedimentary and basaltic
590 rocks occur in the drainage basin.

591 Modified after Galy et al. (2010). Stars indicate the sampling locations of the sediments discussed
592 in this study. See Table 1 for additional information on the location and nature of the different
593 samples.

594

595

Figure 1



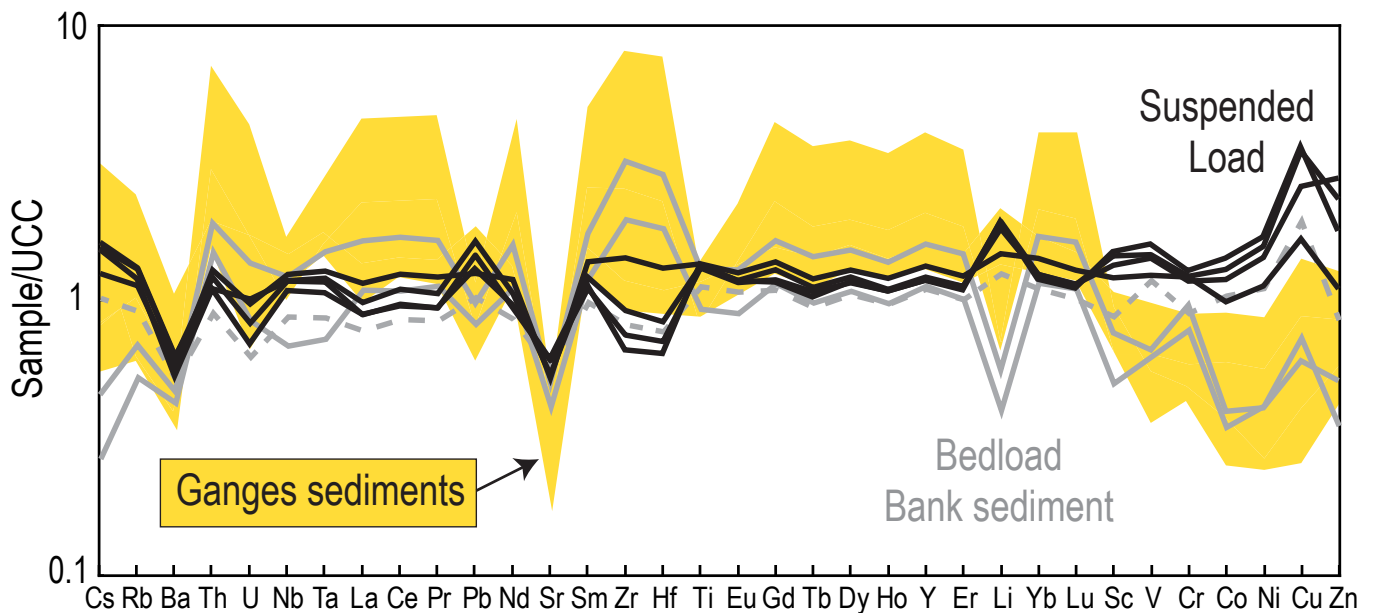
596 **Figure 2:** Trace element patterns of the Yamuna and Chambal sediments normalized to the
597 composition of the upper continental crust (UCC) of Rudnick and Gao (2003).

598 Bedloads and bank sediment are shown with grey lines while suspended loads are shown with black
599 lines. The yellow field indicates the range of concentrations measured in the Ganges sediments in
600 Bangladesh (data from Garçon et al. 2013a, see Table 1). The dashed gray line shows the trace
601 element pattern of the outlier bank sediment BR 938 that resembles a suspended load.

602

Figure 2

603



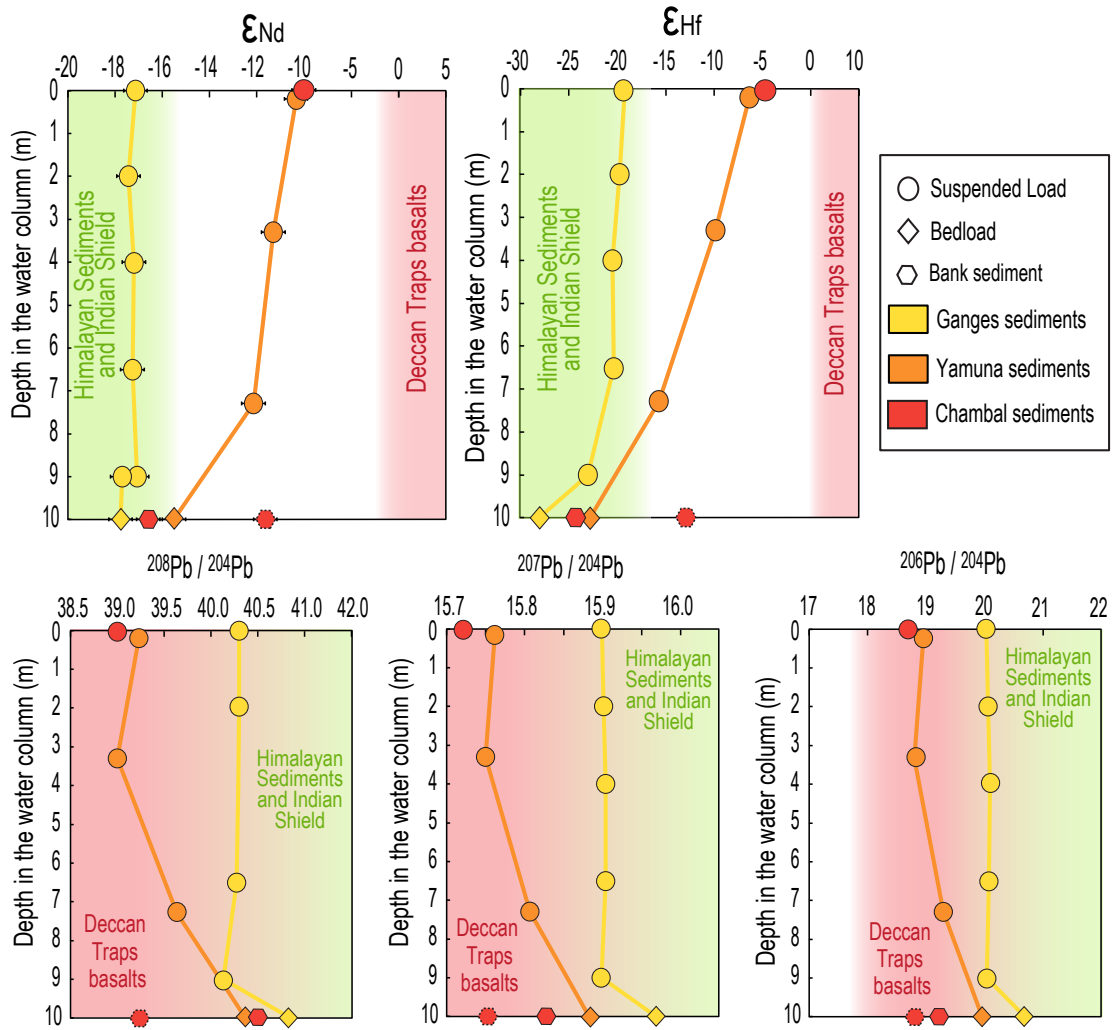
604 **Figure 3:** Nd, Hf and Pb isotopic variations of sediments sampled at different water depths in the
605 Ganges, Yamuna and Chambal Rivers.

606 For the Ganges sediments, only samples recovered along the depth profile are shown in the
607 diagrams (see Table 1; data from Garçon et al. 2013a, 2013b). The ranges of Nd, Hf and Pb isotopic
608 ratios for all Himalayan sediments i.e. samples from the Ganges but also its major tributaries
609 collected at different locations in the floodplain, from the Himalayan mountain front to the delta in
610 Bangladesh are indicated by the green fields (data from Garçon et al. 2013a, 2013b). Red fields
611 show the Nd, Hf and Pb isotopic compositions of the northern Deccan Traps basalts (data from the
612 GEOROC database). River bank sediments are plotted at an arbitrarily depth of 10m. The dashed
613 hexagon corresponds to the outlier bank sediment BR 938. ϵ_{Nd} and ϵ_{Hf} were calculated using the
614 CHUR composition of Bouvier et al. (2008). Analytical errors are smaller than the symbol size
615 except for Nd isotopes (horizontal bars at $\pm 0.5 \epsilon$ units).

616

617

Figure 3

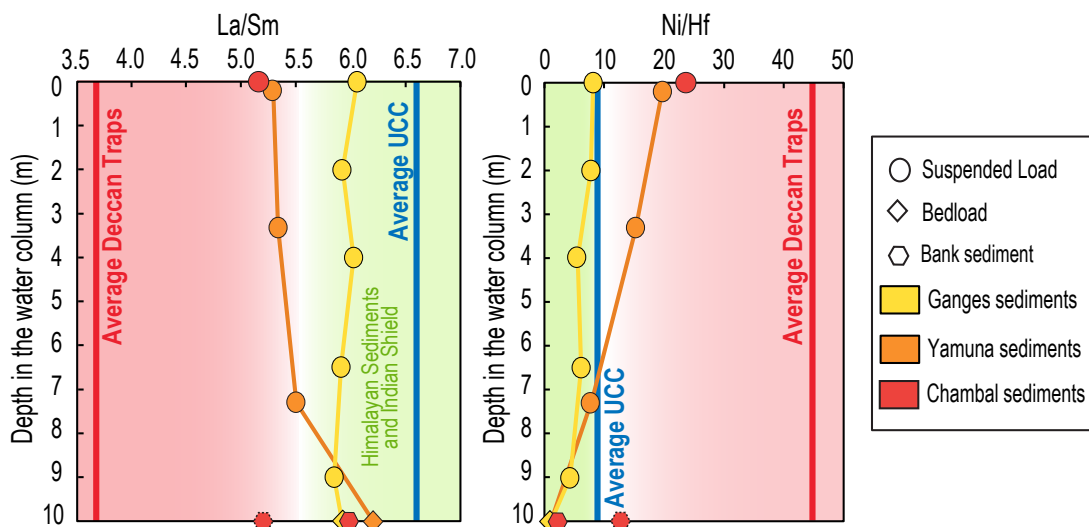


640 **Figure 4:** Variation of the La/Sm and Ni/Hf ratios as a function of depth for the Ganges, Chambal
641 and Yamuna sediments.

642 As in Figure 3, only the Ganges sediments recovered along the depth profile are shown in the
643 diagrams (see Table 1). Data for Himalayan sediments and Indian shield (green fields) are from
644 Garçon et al. (2013a, 2013b). Blue vertical lines show the average La/Sm and Ni/Hf ratios for the
645 upper continental crust (UCC) of Rudnick and Gao (2003). The red vertical line and the red field
646 represent the average value and the range of values known for the northern Deccan Traps (data
647 from the GEOROC database). River bank sediments were plot at an arbitrarily depth of 10m in
648 each diagram. The dashed hexagon corresponds to the outlier bank sediment BR 938.

649

650 **Figure 4**



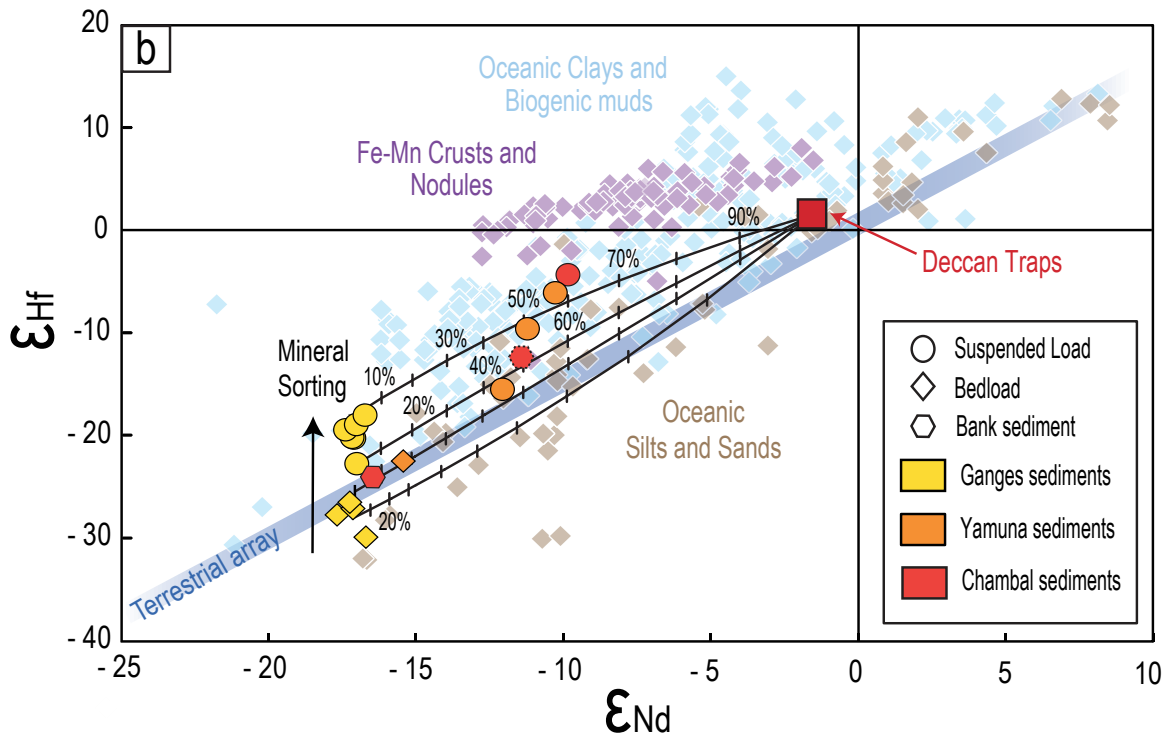
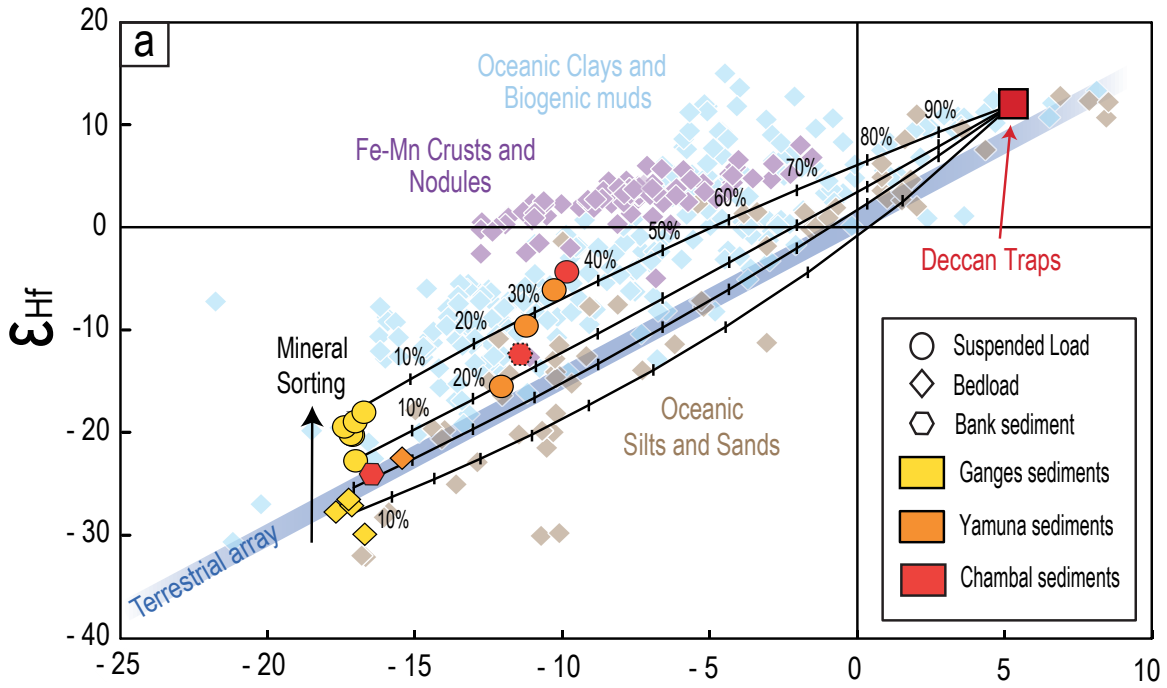
651 **Figure 5:** ϵ_{Nd} and ϵ_{Hf} diagrams showing the composition of the Ganges, Yamuna and Chambal
652 sediments.

653 Black lines correspond to mixing curves between the Deccan Traps basalts and the sediments
654 sampled at different water depths in the Ganges River in Bangladesh. Mixing calculations were
655 performed using two extreme compositions for the Deccan Traps (see panel a) and b)). Ticks (every
656 10%) and associated numbers indicate the proportion of Deccan Traps basalts in the mixtures. The
657 composition of the different endmembers used to calculate the mixing hyperbolas are summarized
658 in Supplementary Table 2. The dashed hexagon corresponds to the outlier bank sediment BR 938
659 having Nd-Hf isotopic compositions similar to suspended loads. The present-day Terrestrial Array
660 is that of Vervoort et al. (2011). Nd-Hf isotopic compositions of worldwide oceanic sediments are
661 also shown. Data for Fe-Mn crusts and nodules are from Albarède et al. (1998), Godfrey et al.
662 (1997), David et al. (2001), Van De Flierdt et al. (2006) and Albarède et al. (1997); oceanic clays
663 and biogenic muds are from Bayon et al. (2009), McLennan et al. (1990), Ben Othman et al. (1989),
664 Vervoort et al. (1999), White et al. (1986), Vlastélic (2005), Pearce et al. (1999), Woodhead et al.
665 (2001), Prytulak et al. (2006), Carpentier et al. (2009), Chauvel et al. (2009), Vervoort et al. (2011)
666 and Carpentier et al. (2008); finally, oceanic silts and sands are from Carpentier et al. (2008),
667 Carpentier et al. (2009), McLennan et al. (1990), Vervoort et al. (1999), Bayon et al. (2009),
668 Prytulak et al. (2006) and Vervoort et al. (2011). All ϵ_{Nd} and ϵ_{Hf} were recalculated using the CHUR
669 composition of Bouvier et al. (2008). Analytical errors are smaller than the symbol size.

670

671

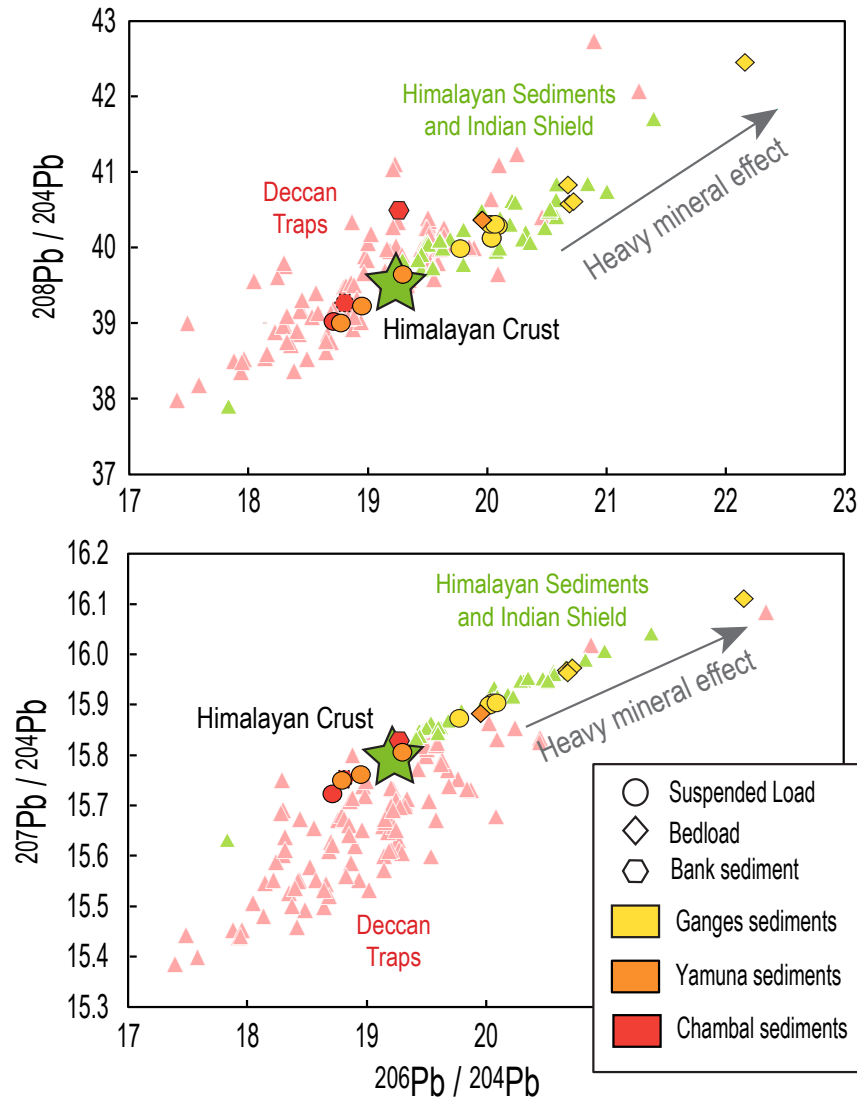
Figure 5



695 **Figure 6:** Pb isotopic compositions of the Ganges, Yamuna and Chambal sediments.
 696 Red triangles represent northern Deccan Traps basalts (data from the GEOROC database) while
 697 green triangles show the compositions of Himalayan sediments and Indian shield (data from
 698 Garçon et al., 2013b). The green star indicates the composition of the upper Himalayan crust as
 699 estimated by Garçon et al. (2013b). The dashed hexagon corresponds to the outlier bank sediment
 700 BR 938. Analytical errors are smaller than the symbol size.

701

Figure 6



Supplementary Table 1: Trace-element concentrations measured in rock standards (ppm)

	BR reference	BR 24 reference	Average measured BEN		BEN		Average measured JSd-2		JSd-2	
	<i>Chauvel et al. (2011)</i>	<i>Chauvel et al. (2011)</i>	measured BEN n=4	2 σ (%)	<i>Chauvel et al. (2011)</i>	Diff (%)	measured JSd-2 n=6	2 σ (%)	<i>Chauvel et al. (2011)</i>	Diff (%)
Li	15.1	7.15	13.2	7.5	13.0	1.5	22.6	2.7	22.1	2.3
Sc	22.8	25.9	22.6	3.6	22.5	0.4	17.4	2.1	17.9	-2.8
Ti	15300	17500	15382	3.5	15400	-0.1	3531	1.7	3570	-1.1
V	226	267	223	1.7	226	-1.2	124	1.2	126	-1.6
Cr	338	425	335	0.7	340	-1.4	100	1.0	106	-5.7
Co	56.6	52.6	59.0	0.8	60.0	-1.7	47.0	1.2	47.5	-1.1
Ni	259	238	256	0.3	258	-0.9	89.2	0.9	91.1	-2.1
Cu	68.8	37.0	64.5	4.0	69.3	-6.9	1061	4.6	1060	0.1
Zn	158	109	122	4.5	119	2.4	2138	0.9	1980	8.0
Rb	46.6	80.0	46.6	3.0	46.8	-0.5	25.6	1.3	25.8	-0.8
Sr	1340	607	1373	2.1	1380	-0.5	211	2.4	210	0.5
Y	28.9	28.5	28.8	0.7	29.0	-0.5	18.3	0.8	18.2	0.5
Zr	273	294	272	2.4	274	-0.6	107	0.5	103	3.9
Nb	115	38.1	119	4.9	116	2.6	4.44	1.8	4.19	6.0
Cs	0.82	0.648	0.75	5.1	0.752	-0.3	1.07	3.1	1.05	1.9
Ba	1090	390	1040	1.4	1050	-1.0	1225	3.3	1230	-0.4
La	82.6	33.6	82.5	0.8	83.0	-0.5	11.5	0.6	10.8	6.5
Ce	155	73.9	156	2.8	155	0.4	24.6	0.8	22.1	11.3
Pr	17.4	9.61	17.4	2.3	17.4	-0.1	3.08	1.1	2.94	4.8
Nd	66.4	39.9	66.1	2.3	67.0	-1.3	12.7	1.9	12.1	5.0
Sm	12.2	8.36	12.2	2.8	12.2	-0.2	2.97	2.1	2.86	3.8
Eu	3.66	2.53	3.66	2.3	3.67	-0.3	0.848	3.2	0.872	-2.8
Gd	9.88	7.28	9.87	1.0	9.87	0.0	3.14	2.0	2.85	10.2
Tb	1.25	1.03	1.25	2.9	1.26	-0.5	0.482	2.6	0.465	3.7
Dy	6.42	5.77	6.44	1.7	6.44	0.0	3.08	3.5	3.04	1.3
Ho	1.08	1.05	1.08	1.2	1.08	0.1	0.647	0.8	0.641	0.9
Er	2.58	2.70	2.59	0.8	2.59	-0.1	1.93	1.8	1.91	1.0
Yb	1.84	2.13	1.83	1.4	1.84	-0.4	1.94	1.9	1.91	1.6
Lu	0.246	0.297	0.241	2.4	0.245	-1.8	0.288	1.6	0.288	0.0
Hf	5.67	6.75	5.64	2.3	5.64	0.1	2.63	1.8	2.74	-4.0
Ta	5.55	2.34	5.98	2.4	5.57	7.3	0.366	2.7	0.345	6.1
Pb	4.77	3.69	4.52	4.9	4.17	8.3	166	0.6	154	7.8
Th	10.7	4.75	10.7	1.5	10.7	0.1	2.65	1.3	2.43	9.1
U	2.39	1.20	2.37	3.0	2.39	-0.7	1.09	1.2	1.09	0.0

Standard deviations (2 σ) were calculated between the n measurements of the rock standards analysed as unknown samples and calibrated to the BR or BR 24 standards using the reference values of Chauvel et al. (2011). Differences between the published values and our measurements (Diff) are also reported in percentage. Note that differences between measured and published values are >5% for some elements in JSd-2. We attribute these differences to the heterogeneity of the standard (see Chauvel et al., 2011 and the GEOREM database for further details).

Supplementary Table 2: Endmembers for Nd-Hf isotopic mixings

	Hf (ppm)	ϵ_{Hf}	Nd (ppm)	ϵ_{Nd}
Ganges surface suspended load	4.5	-18.2	34	-17.2
Ganges intermediate suspended load	6	-23.1	34	-17.2
Ganges deep suspended load	7	-25.6	34	-17.2
Ganges bedload	14	-28.1	54	-17.2
Deccan Traps (Figure 5b) Low radiogenic endmember	4	1.6	20	-1.5
Deccan Traps (Figure 5a) Radiogenic endmember	4	11.8	20	5.3

The composition of the different mixing endmembers were constrained using the data of Garçon et al. (2013b) for the Ganges sediments and the data from Sen et al. (2009), Peng et al. (1998) and the GEOROC database for the Deccan Traps

Peng, Z.X., Mahoney, J.J., Hooper, P.R., Macdougall, J.D., and Krishnamurthy, P., 1998, Basalts of the northeastern Deccan Traps, India: isotopic and elemental geochemistry and relation to southwestern Deccan stratigraphy: *Journal of Geophysical Research*, v. 103, no. B12, p. 29,843–29,865.

Sen, G., Bizimis, M., Das, R., Paul, D.K., Ray, A., and Biswas, S., 2009, Deccan plume, lithosphere rifting, and volcanism in Kutch, India: *Earth and Planetary Science Letters*, v. 277, no. 1-2, p. 101–111, doi: 10.1016/j.epsl.2008.10.002