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# Constraints from loess on the Hf-Nd isotopic composition of the upper continental crust

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25 **Abstract**

26 Knowledge of the average composition of the upper continental crust is crucial to  
27 establish not only how it formed but also when. While well constrained averages  
28 have been suggested for its major and trace element composition, no values exist  
29 for its Nd and Hf isotopic compositions even though radiogenic isotopic systems  
30 provide valuable information on its average model age.

31 Here we present Nd and Hf isotopic data determined on a large number of loess  
32 deposits from several continents. We demonstrate that these deposits have very  
33 uniform Nd and Hf isotopic compositions. We obtain an average Nd isotopic  
34 composition that is similar to previous estimates for the upper continental crust  
35 ( $\epsilon_{Nd} = -10.3 \pm 1.2$  ( $1\sigma$ )) and we establish a new Hf average value at  $\epsilon_{Hf} = -13.2 \pm 2$   
36 ( $1\sigma$ ). This average falls on the “Terrestrial Array”, demonstrating that the two  
37 parent-daughter ratios are not decoupled during crust formation. Trace element  
38 data acquired on the same set of samples allow us to calculate an average  
39  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio for the upper continental crust:  $0.1193 \pm 0.0026$ , a value  
40 slightly higher than previous estimates. Based on the relationship between  
41 Sm/Nd and Nd isotopes, we estimate the average Nd extraction age of upper  
42 continental crust from the depleted mantle at  $T_{DM}(\text{Nd}) = 1.82 \pm 0.07$  Ga. This  
43 model age is entirely consistent with previous suggestions made for example by  
44 Goldstein et al. [1984].

45 Assuming that for each individual sample, the Hf model age cannot be younger  
46 than the Nd model age, our new Nd-Hf isotopic data provide a value for the very  
47 poorly known  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of the upper crust. Our estimate is  $^{176}\text{Lu}/^{177}\text{Hf} =$   
48  $0.0125 \pm 0.0018$ , a value significantly lower than commonly used values [0.0150 –  
49 0.0159, *Griffin et al.*, 2002; *Goodge and Vervoort*, 2006; *Hawkesworth et al.*, 2010]  
50 but higher than Rudnick and Gao’s [2003] estimate of 0.0083. The impact of our  
51 new  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio on crustal model ages of zircon populations is not simple to  
52 evaluate but the Hf model ages calculated with this new Lu/Hf ratio could be  
53 younger by up to 500 Ma.

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## 59 **1 - Introduction**

60 The formation of the continental crust was certainly one of the most important  
61 events that affected the overall composition of the Earth, because the isolation at  
62 the surface of a light and enriched layer left behind a depleted residue in the  
63 mantle. This observation explains why so many studies concentrate on the  
64 processes that produce continental crust and on the timing of crustal growth  
65 [e.g., *Armstrong, 1968; McCulloch and Wasserburg, 1978; Armstrong, 1981;*  
66 *Allègre and Rousseau, 1984; Goldstein et al., 1984; Taylor and McLennan, 1985;*  
67 *Condie, 1993; Wedepohl, 1995; Gallet et al., 1998; Vervoort et al., 2000; Griffin et*  
68 *al., 2002; Rudnick and Gao, 2003; Harrison et al., 2005; Hawkesworth and Kemp,*  
69 *2006; Blichert-toft and Albarède, 2008; Belousova et al., 2010; Hawkesworth et al.,*  
70 *2010; Kemp et al., 2010; Dhuime et al., 2011; Garçon et al., 2011; Iizuka et al.,*  
71 *2013]. In this study, we focus on the information provided by two isotopic*  
72 *systems, Sm-Nd and Lu-Hf. The two systems are strongly coupled during*  
73 *magmatic processes leading to the definition of the “Terrestrial array”, an array*  
74 *along which all terrestrial magmas fall [Vervoort et al., 1999; Vervoort et al.,*  
75 *2011]. However, even though crustal magmas fall on the “Terrestrial Array” the*  
76 *location of the average composition of the continental crust remains unknown.*

77 Knowing the position of present-day average crust on the Terrestrial array is  
78 important because it provides information not only on the processes active  
79 during the formation of the crust but also because the two isotopic systems  
80 record the past history of crustal materials and can be used to calculate an  
81 average extraction age of crust from the mantle. Finally, by using the constraints  
82 provided by the Sm-Nd isotopic system and those coming from the Lu-Hf isotopic  
83 system, we can evaluate the average crustal  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio, a very poorly  
84 known but crucial parameter necessary to calculate crustal residence ages of  
85 zircon populations [e.g., *Griffin et al., 2002; Harrison et al., 2005; Kemp et al.,*

86 2007; *Blichert-toft and Albarède, 2008; Belousova et al., 2010; Kemp et al., 2010;*  
87 *Condie et al., 2011; Yao et al., 2011; Iizuka et al., 2013*].

88 To address all these issues, we focus on a combined Nd and Hf isotopic study of a  
89 variety of recent loess deposits from several continents. Loess deposits result  
90 from the local accumulation of windblown dust coming from usually large  
91 continental areas. They represent natural mixtures of erosion products of  
92 continental surfaces and were therefore used by several previous workers to  
93 determine the average composition of the upper continental crust [e.g., *Taylor*  
94 *and McLennan, 1981; Taylor et al., 1983; Taylor and McLennan, 1985, 1995;*  
95 *Barth et al., 2000*]. We show that they are excellent proxies for the average  
96 composition of large areas of upper continental crust for both the Sm-Nd and the  
97 Lu-Hf isotopic systems. We then suggest an average value for the upper  
98 continental crust for the two systems and we determine an average model age.  
99 Finally, the combined Nd and Hf isotopic data allow us to suggest a value for the  
100  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of the upper continental crust.

101

## 102 **2 - Source of samples**

103 The samples in this study were collected from several locations around the  
104 world: Western Europe, Tajikistan, China and Argentina (see Figure 1). Most  
105 were previously studied by Gallet and co-workers [*Gallet et al., 1996; Gallet et al.,*  
106 *1998; Jahn et al., 2001*] who reported major and trace element data as well as Nd  
107 and Sr isotopic compositions for loess samples from China, Western Europe and  
108 Argentina. The Tajikistan loess deposits come from the Chashmanigar section  
109 and were previously studied by Ding et al. [2002] and by Yang et al. [2006] who  
110 used sedimentological and major element data to constrain climate conditions  
111 during the past 1.8 Ma. However, they did not perform any trace element or  
112 isotopic analyses. Finally, two samples of Sahara dust collected in southern  
113 France were also analyzed.

114 The samples belong to two different types of loess deposits. The Western Europe  
115 Loess samples are periglacial deposits that were produced during the last glacial  
116 period by mechanical erosion of the crust followed by transport by wind over

117 limited distances [*Haase et al.*, 2007]. The situation is rather similar for the  
118 Argentinian loess deposits whose origin is mainly the Andes [*Smith et al.*, 2003].  
119 The Chinese and Tajikistan loess deposits represent much larger volumes and  
120 have a very different origin: the materials come from large desert areas. For the  
121 Chinese loess, particles come mainly from the deserts located Northwest in  
122 Mongolia [*Sun*, 2002]; in southern Tajikistan, the particles originate from the  
123 Karakum and Kyzylkum deserts located northwest in Turkmenistan, Uzbekistan  
124 and Kazakhstan [*Ding et al.*, 2002]. In both cases, the deserts developed on  
125 continental crust that formed over large periods of geological time [e.g., *Lee et al.*,  
126 2011; *Yoshida*, 2012] and particles were transported over long distances by high-  
127 energy winds to accumulate in protected areas [*Ding et al.*, 1999; *Ding et al.*,  
128 2002; *Guo et al.*, 2002]. Consequently, they represent the average composition of  
129 much larger crustal areas than the periglacial deposits. Finally, the dust blown  
130 from the Sahara over Southern France does not constitute a real loess deposit  
131 [*Grousset et al.*, 2003], but it provides valuable information on the average  
132 composition of the largest desert area in the world.

133

### 134 **3 - Analytical techniques**

135 All samples were crushed using an agate mortar. Trace element concentrations  
136 were obtained after dissolution in a HF-HClO<sub>4</sub> mixture using Parr bombs. The  
137 complete procedure is that of Chauvel et al. [2011], but the dissolution time was  
138 increased to insure complete dissolution of the very resistant minerals, an issue  
139 particularly important when using the relationship between REE and Hf  
140 concentrations and when measuring Hf isotopes. Both accuracy and  
141 reproducibility of the data are estimated as better than 5% for most trace  
142 elements, as shown by the analyses of international rocks standards and  
143 duplicate analyses of samples (see Supplementary table).

144 Neodymium and hafnium were isolated from an aliquot of the solution prepared  
145 for trace element analysis and using standard ion-chromatography as described  
146 by Chauvel et al. [2011]. Total procedural blanks were less than 100 picograms  
147 for both Nd and Hf. The Nd and Hf isotopic compositions were measured using  
148 the Nu Plasma HR MC-ICP-MS at ENS Lyon. Mass bias corrections for Nd and Hf

149 isotopic compositions were performed using  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$  and  
150  $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$  respectively. Over the course of analyses, daily averages  
151 obtained for the Nd Ames-Rennes standard ranged between  $0.511958 \pm 19$  and  
152  $0.511976 \pm 14$ , while those obtained for the Hf Ames-Grenoble standard ranged  
153 between  $0.282165 \pm 9$  and  $0.282168 \pm 19$ . All isotopic ratios reported in Table 1  
154 are normalized to the reference values of 0.511961 and 0.282160 as published  
155 by Chauvel and Blichert-Toft [2001] and Chauvel et al. [2011]. Complete  
156 duplicate analyses of several samples show that the reproducibility of isotopic  
157 measurements is better than 100 ppm for both Nd and Hf isotopic ratios (Table  
158 1).

159

#### 160 **4 - Results**

161 New trace element data for the loess are provided in the Supplementary table.  
162 Some samples had been previously analyzed for their trace element contents by  
163 Gallet et al. [1998] and by Jahn et al. [2001] but these were reanalyzed because  
164 some key elements (e.g., Hf) were not measured in many of these older studies.  
165 The new values reported here are generally similar to those previously  
166 published but there are notable exceptions. For example, the new  
167 determinations of REE, Th, Zr and Hf concentrations are systematically higher  
168 than those reported by Jahn et al. [2001] suggesting that dissolution of samples  
169 in 2001 was incomplete, leaving some non-dissolved zircon and monazite grains  
170 (see supplementary figure).

171 Figure 2 shows the trace element patterns obtained for all loess samples. As  
172 previously shown by Gallet et al. [1996] and Jahn et al. [2001], the Chinese loess  
173 are remarkably homogeneous with normalized trace element concentrations  
174 close to the Upper Continental Crust values of Rudnick and Gao [2003] (see  
175 Figure 2b). The new Tajikistan data shown in Figure 2c display similar features.  
176 This is not the case, however, for the periglacial loess sampled in Western  
177 Europe and shown in Figure 2a. The latter samples have much more variable  
178 concentrations and they display large positive Zr-Hf anomalies, most probably  
179 due to the presence of excess zircon. Finally, the Argentinian loess samples and  
180 the two Sahara dust samples shown in Figure 2d have trace element patterns

181 generally parallel to the average upper continental crust (UCC) value, without  
182 positive Zr-Hf anomalies, but with more variability.

183 The Nd and Hf isotopic compositions of all loess samples analyzed in this study  
184 are listed in Table 1. The data are plotted in Figure 3 where they are compared to  
185 data published in the literature for MORB, OIB, oceanic sediments and crustal  
186 rocks. With the exception of the Argentinian samples, all loess define a restricted  
187 range of  $\epsilon_{Nd}$  and  $\epsilon_{Hf}$  values ( $-10.3 \pm 1.2$  and  $-13.8 \pm 4.2$ ) and lie on the terrestrial  
188 array of Vervoort et al. [2011] in the field of crustal materials. The Argentinian  
189 loess have less negative values ( $\epsilon_{Nd} = -1.7$  and  $\epsilon_{Hf} = -2.8$ ), a feature attributed to  
190 the abundance of Andean volcanic rocks in the source area [Gallet et al., 1998;  
191 Smith et al., 2003].

192

## 193 **5 - Discussion**

194 Constraining the average composition of the continental crust is a very active  
195 field of research [e.g., Armstrong, 1968; McCulloch and Wasserburg, 1978;  
196 Armstrong, 1981; Allègre and Rousseau, 1984; Goldstein et al., 1984; Taylor and  
197 McLennan, 1985; Condie, 1993; Wedepohl, 1995; Gallet et al., 1998; Vervoort et  
198 al., 2000; Griffin et al., 2002; Rudnick and Gao, 2003; Hawkesworth and Kemp,  
199 2006; Belousova et al., 2010; Hawkesworth et al., 2010; Dhuime et al., 2011;  
200 Garçon et al., 2011]. Several studies have suggested average values for the upper  
201 continental crust but these mainly focus on its major and trace element  
202 composition (see Rudnick and Gao [2003] for a review). Knowing its radiogenic  
203 isotopic compositions is also important since it provides constraints on the  
204 timing of crust formation through geological time. Several Pb isotope  
205 compositions have been suggested for the upper continental crust [e.g., Zartman  
206 and Doe, 1981; Newsom et al., 1986; Rudnick and Goldstein, 1990; Garçon et al.,  
207 2013b] as well as some average Nd model ages [Allègre and Rousseau, 1984;  
208 Goldstein et al., 1984; Goldstein and Jacobsen, 1988; Jacobsen, 1988]. These show  
209 that the continental crust formed, on average, about 1.8 to 2 Ga ago. Here, we will  
210 use loess as a proxy to more precisely constrain the Nd and Hf isotopic  
211 composition of average upper continental crust. We will then use these data to  
212 re-evaluate when the upper crust separated from the mantle and use the



213 combined Nd and Hf isotopic data to constrain the Lu/Hf ratio of upper  
214 continental crust. It could be argued that the sample set might not be  
215 representative of average upper crust and we will demonstrate that it is.

216

### 217 **5.1 - Loess: an excellent proxy for the average upper continental crust Nd** 218 **isotopic ratio**

219 Loess has been widely used by Taylor and McLennan [1985] to establish the  
220 average REE composition of the upper continental crust because these sediments  
221 represent the average composition of large surface areas. Since the REE content  
222 is representative of the upper continental crust, loess can be used to evaluate its  
223 Nd isotopic composition [McCulloch and Wasserburg, 1978; Taylor et al., 1983;  
224 Gallet et al., 1998].

225 The measured Nd isotopic ratios of nearly 50 loess samples are remarkably  
226 uniform and define two groups (Figures 3 & 4). The first comprises only the  
227 Argentinian loess and is relatively radiogenic with an average  $\epsilon_{Nd}$  of -1.7. Gallet et  
228 al. [1998] concluded that the unusual composition of these samples was due to  
229 the overwhelming presence of recent volcanic products coming from the Andes  
230 and could not be considered as representative of large areas of the upper  
231 continental crust. We concur with their conclusion. The second group of samples  
232 consists of all other analyzed loess samples (Figure 3). While the Chinese and  
233 Tajikistan loess have indistinguishable isotopic compositions ( $\epsilon_{Nd} = -9.82 \pm 0.44$   
234 and  $\epsilon_{Nd} = -9.46 \pm 0.36$ , respectively), the two Sahara dusts have lower  $\epsilon_{Nd}$  at -12.4.  
235 Finally, the Western European loess are more heterogeneous and average at  $\epsilon_{Nd}$   
236 =  $-11.25 \pm 1.28$ . We attribute this larger range of isotopic compositions to  
237 processes acting during the formation of periglacial loess, when relatively small  
238 volumes of material were produced by erosion of proximal sources during the  
239 last glacial period. Such small volumes of glacial sediments were not well mixed  
240 by long distance transport and their composition is a function of the diversity of  
241 local terranes in Western Europe. In contrast, the Tajikistan and the Chinese  
242 loess are remarkably homogeneous, a feature consistent with their origin as dust  
243 blown from large desert areas [Ding et al., 1999; Ding et al., 2002]. Nevertheless,

244 taken together, all these samples define a well-constrained average at  $\epsilon_{Nd}=-$   
245  $10.3\pm 1.2$  ( $1\sigma$ ) (see inset of Figure 3).

246 Given the large number of Chinese and Tajikistan samples in our data set, it could  
247 be argued that our average  $\epsilon_{Nd}$  value is only representative of the upper  
248 continental crust present in Russia and Central Asia. However, similar  $\epsilon_{Nd}$  values  
249 have been reported for all sorts of other areas in the world: The Carpathian loess  
250 deposits in Eastern Europe have an average  $\epsilon_{Nd}$  value at  $-10.21\pm 0.34$  [Újvári *et*  
251 *al.*, 2012] and a placer deposit that averages the area drained by the Rhone River  
252 in Western Europe has an  $\epsilon_{Nd}$  value of  $-9.3$  [Garçon *et al.*, 2011]. This suggests  
253 that most of the European continent has an  $\epsilon_{Nd}$  value at about  $-10$ . The only two  
254 US loess samples analyzed for Nd isotopes have lower values at  $-13$  and  $-15$   
255 [Taylor *et al.*, 1983] which might indicate that the American upper crust could  
256 have a different average value. However, the  $\epsilon_{Nd}$  values reported by Goldstein *et*  
257 *al.* [1984] and Goldstein and Jacobsen [1988] for particulates collected on major  
258 rivers from the American continent do not confirm these low values but provide  
259 a range between  $-20.8$  and  $-4.4$ . Worldwide aerosols can also be used to estimate  
260 the composition of exposed continental crust. Grousset and Biscaye [2005]  
261 compiled the existing data and showed that aerosols have much more variable  
262 compositions than loess or river particulates, but they could estimate that the  
263 world mean  $\epsilon_{Nd}$  value was around  $-11$  [Grousset and Biscaye, 2005]. Finally,  
264 Goldstein *et al.* [1984] analyzed a large number of river sediments and aeolian  
265 dusts from various continents and provided an average  $\epsilon_{Nd}$  value at  $-11.4\pm 4$  for  
266 all these deposits. Given the similarity of all the values listed above, we suggest  
267 that our estimate ( $\epsilon_{Nd}=-10.3$ ) is probably accurate and representative of  
268 continental crust exposed today at the surface of the Earth. Estimating the  
269 uncertainty is more difficult. Here we use the  $1\sigma$  error based on our data set  
270 ( $\pm 1.2$ ) but we acknowledge that with a larger set of samples, the value could  
271 change.

272

273 **5.2 - Loess: also a good proxy for the average upper continental crust Hf**  
274 **isotopic ratio**

275 Several authors have argued that the Zr and Hf contents of loess should not be  
276 used as analogues for their source [*Taylor et al.*, 1983; *Barth et al.*, 2000; *Rudnick*  
277 *and Gao*, 2003]. These arguments are based on the observation that the loess  
278 that they had studied had a very large excess of Zr and Hf relative to the REE, a  
279 feature attributed to the presence of excess zircons. All the samples that they  
280 studied, however, are periglacial loess sediments. Our Western European loess  
281 samples have the same large positive anomaly in Zr and Hf (see Figure 2) and we  
282 argue that many or all periglacial loess deposits contain this feature. In contrast,  
283 the Tajikistan, Chinese and Argentinian loess deposits as well as the Sahara dusts  
284 either have no anomaly or a slight negative anomaly (Figure 2). Since zircons are  
285 rich in Hf and have usually very unradiogenic Hf isotopes, their presence has  
286 strong impact on the whole rock Hf isotopic composition. As a result, the  
287 measured Hf isotopic ratios reported in the Table 1 for the Western European  
288 loess cannot be directly used to establish the average composition of the upper  
289 continental crust. It is, however, possible to correct for the “zircon effect” by  
290 using the relationship between Nd/Hf and  $\Delta\epsilon_{\text{Hf}}$  (the vertical deviation from the  
291 terrestrial array as defined by *Carpentier et al.* [2009]) as shown in Figure 4.  
292 Nd/Hf is well constrained in all estimates of upper continental crust, while  $\Delta\epsilon_{\text{Hf}}$  is  
293 a good measure of mineralogical sorting during sediment formation [*Carpentier*  
294 *et al.*, 2009; *Vervoort et al.*, 2011; *Garçon et al.*, 2013a]. In Figure 4, loess deposits  
295 define a positive correlation. The Western Europe loess have low Nd/Hf (i.e.,  
296 positive Hf anomalies), lie below the terrestrial array of *Vervoort et al.* [2011]  
297 and have negative  $\Delta\epsilon_{\text{Hf}}$  values, as expected by the presence of excess old zircons.  
298 In contrast, the Tajikistan loess samples have relatively high Nd/Hf (i.e., slight  
299 negative Hf anomalies) and slightly positive  $\Delta\epsilon_{\text{Hf}}$  values, as expected for  
300 sediments deficient in zircon relative to their crustal source [*Carpentier et al.*,  
301 2009; *Vervoort et al.*, 2011; *Garçon et al.*, 2013a]. The Chinese and Argentinian  
302 loess have compositions that plot in between these two end members. Using the  
303 values recommended for the Nd/Hf ratio of upper continental crust, we can  
304 therefore estimate the  $\Delta\epsilon_{\text{Hf}}$  value for average upper continental crust. The most  
305 recent estimation of  $(\text{Nd}/\text{Hf})_{\text{UCC}}$  provided by *Rudnick and Gao* [2003] constrains  
306 the  $\Delta\epsilon_{\text{Hf}}$  value for upper continental crust at +1.6 with an error of less than  $\pm 2$ ,  
307 based on the range of estimated  $(\text{Nd}/\text{Hf})_{\text{UCC}}$  (see Figure 4).

308 This  $\Delta\epsilon_{\text{Hf}}$  value translates into an  $\epsilon_{\text{Hf}}$  value of  $-13.2 \pm 2$  ( $1\sigma$ ) using the average  $\epsilon_{\text{Nd}}$   
309 value of  $-10.3$  determined above and the terrestrial array equation of Vervoort et  
310 al. [2011] ( $\epsilon_{\text{Hf}} = 1.55 \cdot \epsilon_{\text{Nd}} + 1.21$ ). Such value is not identical to the average of all  
311 loess measurements ( $-13.8 \pm 4.2$ ) but it is similar and the error on the average is  
312 smaller. These  $\epsilon$  values correspond to a  $^{143}\text{Nd}/^{144}\text{Nd}$  of  $0.512102 \pm 67$  and a  
313  $^{176}\text{Hf}/^{177}\text{Hf}$  of  $0.282412 \pm 56$  (see Table 2).

314 The combined Nd and Hf isotopic values for average upper continental crust  
315 define the point shown as a red star in Figure 3 at  $\epsilon_{\text{Nd}} = -10.3 \pm 1.2$  ( $1\sigma$ ) and  $\epsilon_{\text{Hf}} = -$   
316  $13.2 \pm 2$  ( $1\sigma$ ), an average that plots, within error, on the terrestrial array thereby  
317 supporting the long-standing observation that the parent-daughter ratios Sm/Nd  
318 and Lu/Hf are coupled during magmatic processes both in the mantle and the  
319 crust. It also provides a value for the average upper continental crust, a value  
320 that is very useful in modeling how the continents formed.

321

### 322 **5.3 - Nd model age of upper continental crust**

323 To model the average formation age of the upper continental crust, we need  
324 well-constrained values not only for Nd and Hf isotopic compositions but also for  
325 Sm/Nd and Lu/Hf ratios. Data listed in Table 1 show that both the loess Nd  
326 isotopic compositions and their  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios ( $0.1193 \pm 0.0026$ , recalculated  
327 using the Sm and Nd concentrations) are extremely constant. This feature arises  
328 from the uniform Sm/Nd ratio of most crustal minerals [*Taylor and McLennan,*  
329 *1981; Goldstein et al., 1984; Taylor and McLennan, 1985; Garçon et al., 2011*].  
330 When compared to the  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio recalculated from previously published  
331 UCC estimates [*Taylor and McLennan, 1985; Condie, 1993; Gao et al., 1998;*  
332 *Rudnick and Gao, 2003*], our value is slightly higher ( $0.1193$  vs.  $\approx 0.1050$ ) a  
333 feature that may be related to the poor precision of the Sm and Nd concentration  
334 estimates used in these publications (typically 10%, see Table 2). Our value is  
335 similar, however, to values proposed by Jahn and Condie [*Jahn and Condie, 1995*]  
336 and in studies when the  $^{147}\text{Sm}/^{144}\text{Nd}$  was determined with better precision  
337 [*McCulloch and Wasserburg, 1978; Allègre and Rousseau, 1984; Goldstein et al.,*  
338 *1984*]. Using this value for  $^{147}\text{Sm}/^{144}\text{Nd}$  ( $0.1193 \pm 0.0026$ ), our UCC estimate for

339  $^{143}\text{Nd}/^{144}\text{Nd}$ , the depleted mantle values listed in Table 2 and the following  
340 equation,

$$T_{\text{DM}} = \text{Log} \left( \frac{\left( \frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_{\text{UCC}} - \left( \frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_{\text{DM}}}{\left( \frac{^{147}\text{Sm}}{^{144}\text{Nd}} \right)_{\text{UCC}} - \left( \frac{^{147}\text{Sm}}{^{144}\text{Nd}} \right)_{\text{DM}}} - 1 \right) / \lambda$$

341 (with  $\lambda=6.54 \cdot 10^{-12} \text{ year}^{-1}$ ) we can calculate a model age for the extraction of the  
342 crust from the depleted mantle.

343 We obtain a Nd model age of  $1.82 \pm 0.07 \text{ Ga}$  ( $1\sigma$ ) for the separation of crust from  
344 the mantle. Such value falls within the range of previous estimates based on Nd  
345 isotopes [e.g., *Allègre and Rousseau, 1984; Goldstein et al., 1984; Hawkesworth*  
346 *and Kemp, 2006*], but has a much smaller error than previous estimates.

347 The calculated model age depends heavily on the chosen parameters for the  
348 depleted mantle source. Here, we consider that depletion started at the  
349 beginning of Earth history and we chose a very depleted mantle (see Table 2).  
350 Other authors prefer more subdued values. For example, Gale et al. [2013]  
351 recently provided an estimate based on the average composition of MORB while  
352 Dhuime et al. [2011] suggested that the source of newly formed continental crust  
353 was less depleted than the MORB mantle (see Table 2). When these references  
354 are used, we calculate that the Nd model age of upper continental crust would be  
355 200 Ma younger. An extra complication has been introduced recently by Jackson  
356 and Carlson's [2012] suggestion that the Earth has a superchondritic  
357 composition. Gale et al. [2013] already discussed the issue and showed that a  
358 serious problem occurs because the present-day isotopic composition of a  
359 superchondritic Earth is identical to their estimate of present-day depleted  
360 mantle. Indeed, this leaves no space for the development of a mantle that had  
361 become depleted as a consequence of the extraction of enriched continental  
362 crust. If we accept that the Earth is superchondritic and that the depleted mantle  
363 is more depleted than suggested by Gale et al. [2013], with, for example, a Nd  
364 isotopic composition similar to our chosen estimate (see Table 2), then the entire  
365 mantle would have to be depleted to compensate for the extraction of the  
366 continental crust.

367

#### 368 5.4 - $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of upper continental crust and Hf model age

369 To establish the average Hf model age of the upper continental crust is not as  
370 straightforward as for Nd because the  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of continental crust is  
371 poorly constrained, yet has a major impact on the calculations. In Table 2, we list  
372 estimates of  $^{176}\text{Lu}/^{177}\text{Hf}_{\text{UCC}}$  that have been suggested in the literature. The  
373  $^{176}\text{Lu}/^{177}\text{Hf}$  values calculated using upper crustal Lu and Hf contents range  
374 mostly from 0.0057 to 0.0106 [Shaw *et al.*, 1967; Shaw *et al.*, 1976; Taylor and  
375 McLennan, 1985; Condie, 1993; Wedepohl, 1995; Gao *et al.*, 1998; Rudnick and  
376 Gao, 2003] but higher values have also been suggested: Goodge and Vervoort  
377 [2006] suggest a  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.0150 for new Proterozoic crust, while  
378 Hawkesworth *et al.* [2010] suggested a value of 0.0159 on the basis of over 7000  
379 measurements of granitoids. Finally, Condie and co-workers [Condie *et al.*, 2011]  
380 suggest a value as high as 0.020. The range of suggested values is therefore very  
381 large.

382 Unfortunately, the measured  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios of the loess samples cannot be  
383 used to estimate the  $^{176}\text{Lu}/^{177}\text{Hf}$  of the upper continental crust because loess  
384 deposits are affected by sedimentary processes that sort minerals eroded from  
385 crustal rocks. In contrast to their generally uniform  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios, all  
386 minerals do not have similar  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios, and their relative proportions  
387 strongly influence the whole-rock  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio, which might be quite  
388 different from that of the crustal precursor. One mineral, zircon, is particularly  
389 important because it dominates the whole-rock  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio with its very  
390 high Hf content and its extremely low  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio. In addition, it is very  
391 resistant to alteration processes and survives even extreme weathering. If a high  
392 proportion of old zircon is retained in a loess deposit, then the whole rock has  
393 low  $^{176}\text{Lu}/^{177}\text{Hf}$  and unradiogenic  $^{176}\text{Hf}/^{177}\text{Hf}$ , as is the case with the Western  
394 European loess deposits (see Table 1 and Figure 4). In contrast, if the proportion  
395 of zircon is lower, as is the case for the Tajikistan loess samples, then the  
396  $^{176}\text{Lu}/^{177}\text{Hf}$  is higher and  $^{176}\text{Hf}/^{177}\text{Hf}$  is more radiogenic. Thus, the large range of  
397  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios reported in loess deposits is likely controlled by sedimentary  
398 sorting processes and these values cannot be considered as representative of the  
399  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of the crustal precursors. We therefore use a different

400 approach that combines the constraints provided by the Sm-Nd and Lu-Hf  
401 isotopic systems to determine the best estimate for the upper continental crust  
402 Lu/Hf ratio.

403 In Figure 5, we plot Hf model ages of individual loess samples as a function of  
404 their Nd model age. For each sample, we use the measured  $^{147}\text{Sm}/^{144}\text{Nd}$  and  
405  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios as well as the depleted mantle values shown with an asterisk  
406 in Table 2. To calculate the Hf crustal model ages, we used the measured  
407  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios together with a range of  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios as published for  
408 upper continental crust, and the depleted mantle values shown with an asterisk  
409 in Table 2. Because the range of possible  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios in average upper  
410 crust (between 0.0057 and 0.0200, see Table 2) is very large, it introduces a very  
411 large range of possible Hf model ages  $T_{\text{DM}}(\text{Hf})$  (shown by vertical lines in Figure  
412 5). If the upper crust has a high  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.0200, as suggested by  
413 Condie et al. [2011], then the  $T_{\text{DM}}(\text{Hf})$  of all loess (excluding the Argentinian  
414 loess) averages  $2.47 \pm 0.13$  Ga, a value that is 600 Ma older than the average Nd  
415 model age ( $1.82 \pm 0.07$  Ga); if the crustal  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio is 0.0159, as suggested  
416 by Hawkesworth et al. [2010], then the  $T_{\text{DM}}(\text{Hf})$  average at  $2.05 \pm 0.11$  Ga, still  
417 over 200 Ma older than the average Nd model age. In contrast, using a low  
418  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio at 0.0057 provides much younger Hf model ages ( $1.45 \pm 0.08$   
419 Ga). Finally, a  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.0083, as suggested by Rudnick and Gao  
420 [2003], gives an average Hf model age of  $1.57 \pm 0.09$  Ga.

421 Considering the overall geochemical behavior of REE and Zr-Hf during magmatic  
422 and sedimentary processes [Vervoort and Patchett, 1996; Vervoort and Blichert-  
423 Toft, 1999; Vervoort et al., 1999; Chauvel et al., 2008; Carpentier et al., 2009;  
424 Vervoort et al., 2011], it seems unlikely that the Nd model age of upper  
425 continental crust should be older than its Hf model age. The opposite is, in fact,  
426 much more likely because most Hf present in crustal materials is sequestered in  
427 zircon, a mineral phase that is extremely robust during alteration and reworking  
428 of continental crust.

429 To constrain the  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of the upper continental crust, we assume here  
430 that  $T_{\text{DM}}(\text{Hf})$  and  $T_{\text{DM}}(\text{Nd})$  should be identical for each individual loess and dust  
431 sample and we calculate the necessary  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio for each individual

432 sample. Results of the calculation are shown in Figure 6 where they are also  
433 compared to the range of suggested values from literature. On average, we  
434 estimate that the  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of upper continental crust is  $0.0125\pm 0.0018$   
435 ( $1\sigma$ ).

436 In summary, the loess data suggest that the average model age of upper  
437 continental crust is  $1.82\pm 0.07$  Ga ( $1\sigma$ ) based on Nd isotopes. Assuming that Hf  
438 model ages cannot be any younger than Nd model ages, the loess data also  
439 provide constraints on the  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of upper continental crust, which  
440 cannot be smaller than  $0.00125 \pm 0.0018$ , the value that corresponds to  
441 concordant  $T_{\text{DM}}(\text{Hf})$  and  $T_{\text{DM}}(\text{Nd})$  ages. Higher values, such as those suggested  
442 previously by other authors [*Goodge and Vervoort, 2006; Hawkesworth et al.,*  
443 *2010*] are also plausible, but would result in an average upper crust  $T_{\text{DM}}(\text{Hf})$  age  
444 over 200 Ma older than the  $T_{\text{DM}}(\text{Nd})$  age.

445

## 446 **6 - Conclusions**

447 Our Nd-Hf isotopic study of a large number of loess samples provides new  
448 constraints on the average isotopic composition of the upper continental crust.  
449 We estimate that present-day upper continental crust has the following  
450 characteristics:  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512101\pm 60$  and  $^{176}\text{Hf}/^{177}\text{Hf} = 0.282412\pm 60$ . Using  
451 the bulk silicate Earth values determined by Bouvier et al. [2008], these isotopic  
452 ratios translate into  $\epsilon_{\text{Nd}} = -10.3\pm 1.2$  ( $\pm 1\sigma$ ) and  $\epsilon_{\text{Hf}} = -13.2\pm 2$  ( $\pm 1\sigma$ ) and fall within  
453 error on the terrestrial array of Vervoort et al. [2011].

454 The uniform  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio ( $0.1193\pm 0.0026$ ) of loess deposits can also be  
455 considered as representative of the upper continental crust value. Combining the  
456 parent/daughter ratio with the average Nd isotopic composition, we calculate  
457 that the average Nd model age of upper continental crust is  $1.82\pm 0.07$  Ga.

458 Finally, we constrain the  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of the upper continental crust using  
459 the relationship between Hf and Nd isotopes. Our preferred estimate  
460 corresponds to  $0.0125\pm 0.0018$ , a value that is significantly higher than most  
461 previous estimates but lower than the ratio suggested by Goodge and Vervoort  
462 [2006] and Hawkesworth et al. [2010]. We emphasize that 0.0125 represents the



463 lower limit for  $^{176}\text{Lu}/^{177}\text{Hf}$  because any lower estimate makes the Hf model ages  
464 younger than the Nd model ages, a very unlikely situation given the geochemical  
465 behavior of Hf and REE. The impact of this new  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio on crustal  
466 differentiation ages of zircon populations such as those calculated by numerous  
467 authors [e.g., *Griffin et al.*, 2002; *Harrison et al.*, 2005; *Kemp et al.*, 2007; *Blichert-*  
468 *toft and Albarède*, 2008; *Wang et al.*, 2009; *Belousova et al.*, 2010; *Kemp et al.*,  
469 2010; *Yao et al.*, 2011; *Iizuka et al.*, 2013] is quite variable, but the ages can be  
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471

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723

724

725 **Table captions:**

726

727 **Table 1:** Nd and Hf isotopic results for all loess samples.

728 Footnotes: All  $\epsilon_{Nd}$  and  $\epsilon_{Hf}$  values were calculated using the BSE value suggested  
729 by Bouvier et al. [2008]. Dup stands for complete duplicate analyses. The  
730  $^{147}Sm/^{144}Nd$  and  $^{176}Lu/^{177}Hf$  are calculated using the Sm, Nd, Lu and Hf  
731 concentration data listed in the Supplementary table.

732

733 **Table 2:** Compilation of the parent-daughter ratios and Nd and Hf isotopic  
734 compositions of various reservoirs.

735 Footnotes: Numbers in italics correspond to ratios recalculated using published  
736 concentrations. \*: values used to calculate  $T_{DM}$ . Data sources: Allègre and  
737 Rousseau [1984], Bouvier et al. [2008], Chauvel et al. [2008], Condie [1993],  
738 Condie et al. [2011], Dhuime et al. [2011], Gale et al. [2013], Gao et al. [1998],  
739 Goldstein et al. [1984], Goodge and Vervoort [2006], Griffin et al. [2002],  
740 Hawkesworth et al. [2010], Jahn and Condie [1995], McCulloch and Wasserburg  
741 [1978], Rudnick and Gao [2003], Salters and Stracke [2004], Shaw et al. [1967;  
742 1976], Taylor and McLennan [1985] and Wedepohl [1995].

743

744 **Supplementary table:** Trace element concentrations measured on all loess  
745 samples as well as values published by Gallet et al. [1996] for the Luochuan loess.

746 **Supplementary figure:** Comparison between the new trace element data and  
747 the data published previously by Jahn et al. [2001].

748

749 **Figure captions:**

750 **Figure 1:** Map of the world showing the location of loess deposits. The precise  
751 locations of Western European, Chinese, Argentinian and Tajikistan loess  
752 samples were provided by Gallet et al. [1996; 1998], Jahn et al. [2001] and Ding  
753 et al. [2002]. The Sahara samples blown over Southern Europe were collected  
754 close to Grenoble and at 2900 m altitude in the Alps. Latitudes and longitudes are  
755 given in the Supplementary Table.

756

757 **Figure 2:** Trace element patterns of the loess samples. All concentrations are  
758 normalized to the upper continental crust average of Rudnick and Gao [2003]. a)  
759 Western European loess, b) all Chinese loess including data published by Gallet  
760 et al. [1996], c) Tajikistan loess and d) Argentinian loess and Sahara dust.

761

762 **Figure 3:** Nd and Hf isotopic compositions of loess samples.  $\epsilon_{Nd}$  and  $\epsilon_{Hf}$  were  
763 calculated using the BSE value of Bouvier et al. [2008]. The terrestrial array  
764 corresponds to  $\epsilon_{Hf} = 1.55 \cdot \epsilon_{Nd} + 1.21$  as recently compiled by Vervoort et al. [2011].  
765 Data for MORB and OIB were compiled using the PetDB and Georoc databases  
766 and also include some unpublished values of Chauvel. Oceanic sediments plotted  
767 here were published in the literature [*White and Dupré, 1986; BenOthman et al.,*  
768 *1989; McLennan et al., 1990; Godfrey et al., 1997; Albarède et al., 1998; Pearce et*  
769 *al., 1999; Vervoort et al., 1999; David et al., 2001; Woodhead et al., 2001; Vlastelic*  
770 *et al., 2005; Prytulak et al., 2006; van de Flierdt et al., 2007; Carpentier et al.,*  
771 *2008; Bayon et al., 2009; Carpentier et al., 2009; Chauvel et al., 2009; Vervoort et*  
772 *al., 2011*]. Data source for continental crust were published by Vervoort and  
773 Patchett [1996] and by Vervoort et al. [1999; 2000]. The inset shows how our  
774 estimated upper continental crust composition (red star) relates to the range of  
775 known isotopic values in the Earth.

776

777 **Figure 4:** Nd/Hf versus  $\Delta\epsilon_{Hf}$  for all the analyzed loess samples. The inset shows  
778 schematically how the  $\Delta\epsilon_{Hf}$  values are calculated for each sample. The terrestrial  
779 array used to calculate  $\Delta\epsilon_{Hf}$  values corresponds to  $\epsilon_{Hf} = 1.55 \cdot \epsilon_{Nd} + 1.21$  as recently  
780 reevaluated by Vervoort et al. [2011]. Shown by arrows along the horizontal axis  
781 are various estimates for Upper Continental Crust: Taylor and McLennan [1985],  
782 Shaw et al. [1967; 1976], Rudnick and Gao [2003], Condie [1993] and Gao et al.  
783 [1998].

784

785

786 **Figure 5:**  $T_{DM}$  (Nd) versus  $T_{DM}$  (Hf) for all loess samples.

787 The  $T_{DM}$  (Nd) are calculated using the  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio measured for each  
788 sample. They are well constrained with an error smaller than the horizontal bars.  
789 The  $T_{DM}$  (Hf) ages are calculated using a single stage Lu/Hf evolution for the  
790 samples coming from China, Tajikistan, Argentina and Sahara, and using a two  
791 stages evolution for the samples from Western Europe. For the latter, we  
792 assumed that the average crystallization age of the excess zircons was 0.9 Ga, an



793 age consistent with the Archean to Proterozoic materials that have been  
794 repeatedly reworked during the Cadomian and Hercynian orogenies [*Peucat et*  
795 *al.*, 1988]. For all samples, the vertical bar corresponds to the range of ages  
796 obtained with a  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio going from 0.0057 (the youngest ages) to  
797 0.0200 (the oldest ages). The inset shows how the two-stages calculation  
798 operates. A “zircon stage” is calculated between present-day and a crystallization  
799 age  $T_{\text{cryst}}$  of 900 Ma, and using a  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.0001. Prior to  $T_{\text{cryst}}$ , the  
800 evolution follows the same range of UCC  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios as for all other  
801 samples. The inset also highlights how single stage crustal model ages become  
802 significantly too old if the zircons did not crystallize recently.

803

804 **Figure 6:** Measured  $^{147}\text{Sm}/^{144}\text{Nd}$  versus calculated  $^{176}\text{Lu}/^{177}\text{Hf}$  for all loess  
805 samples.

806 As in Figure 5, a single stage history is assumed for the Argentinian, Chinese,  
807 Tajikistan and Sahara samples and a two-stages history for the Western  
808 European samples. The grey field corresponds to the range of published values  
809 for the Lu/Hf ratio of upper continental crust [*Shaw et al.*, 1967; *Taylor and*  
810 *McLennan*, 1985; *Condie*, 1993; *Gao et al.*, 1998; *Griffin et al.*, 2002; *Rudnick and*  
811 *Gao*, 2003; *Goodge and Vervoort*, 2006; *Hawkesworth et al.*, 2010; *Condie et al.*,  
812 2011]. The two red lines show our estimated averages and the orange fields  
813 correspond to the calculated error at  $1\sigma$ .

814

## Highlights

- First estimate of the average Nd-Hf isotopic composition of upper continental crust
- The average ( $\epsilon_{\text{Nd}} = -10.3 \pm 1.2$  and  $\epsilon_{\text{Hf}} = -13.2 \pm 2$ ) falls on the terrestrial array
- The average Nd model age of upper continental crust is  $1.82 \pm 0.07$  Ga
- The upper continental crust  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio is  $0.0125 \pm 0.0018$

Figure 1

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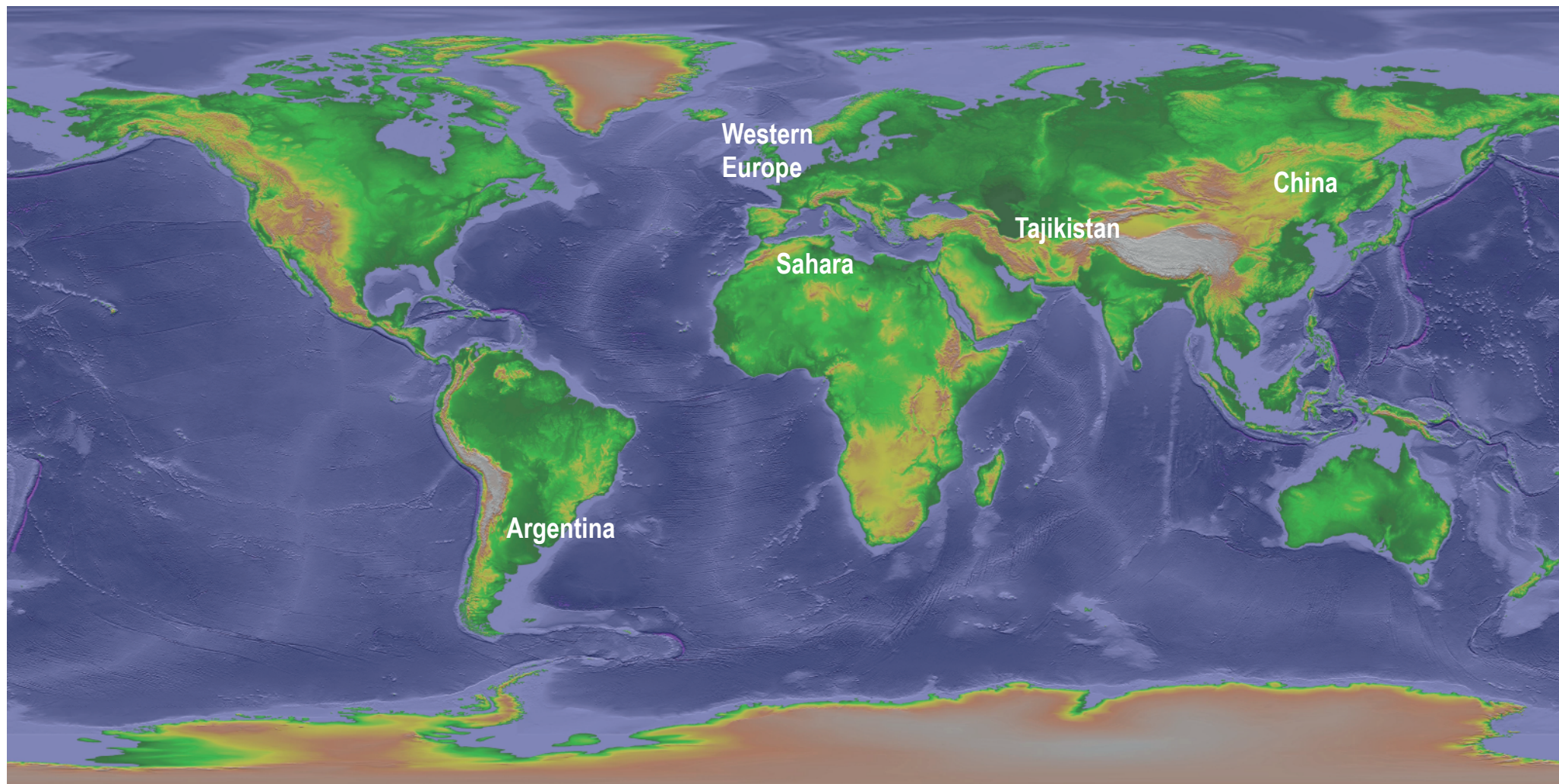


Figure 1

Figure 2

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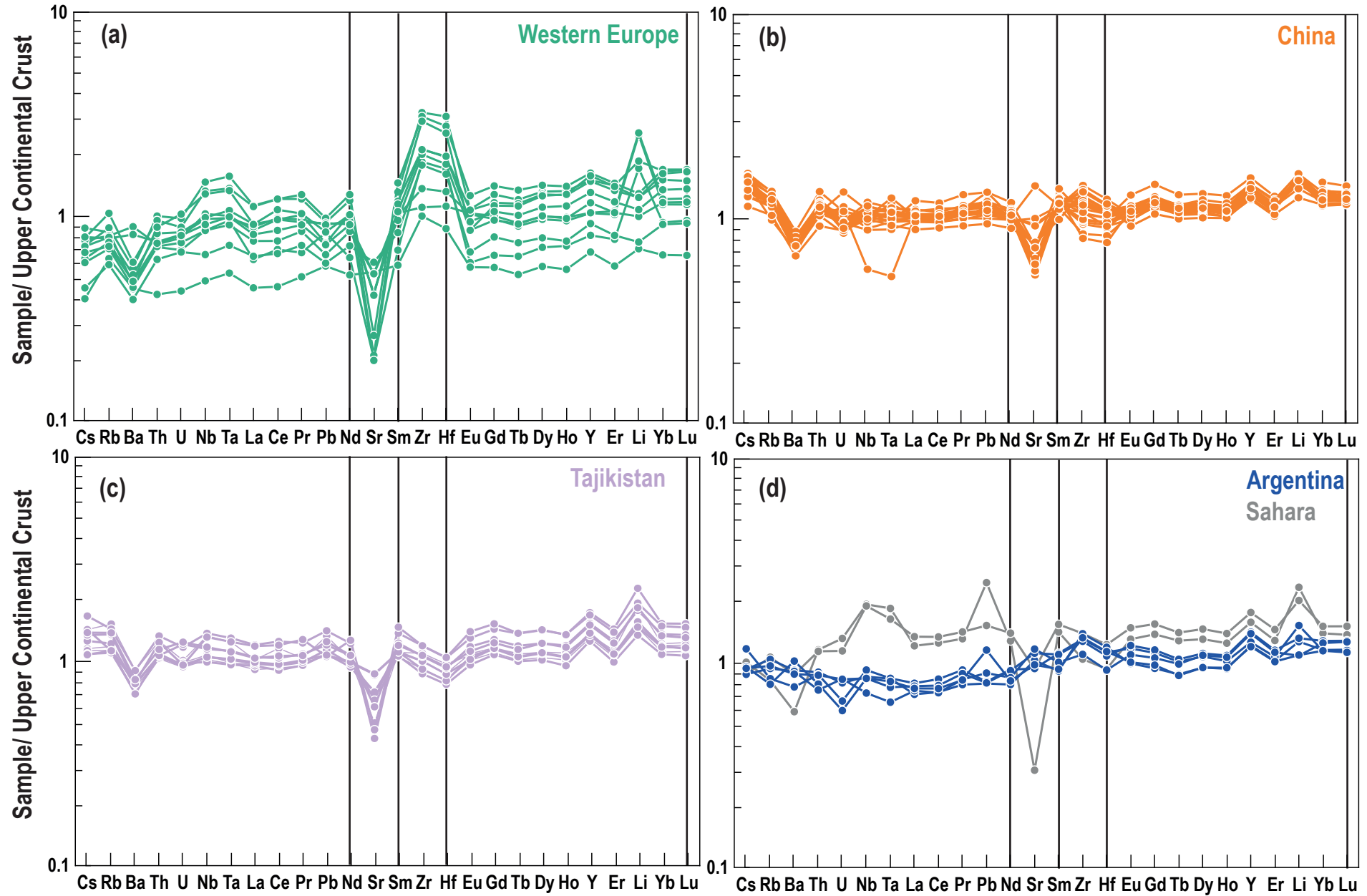


Figure 2

Figure 3

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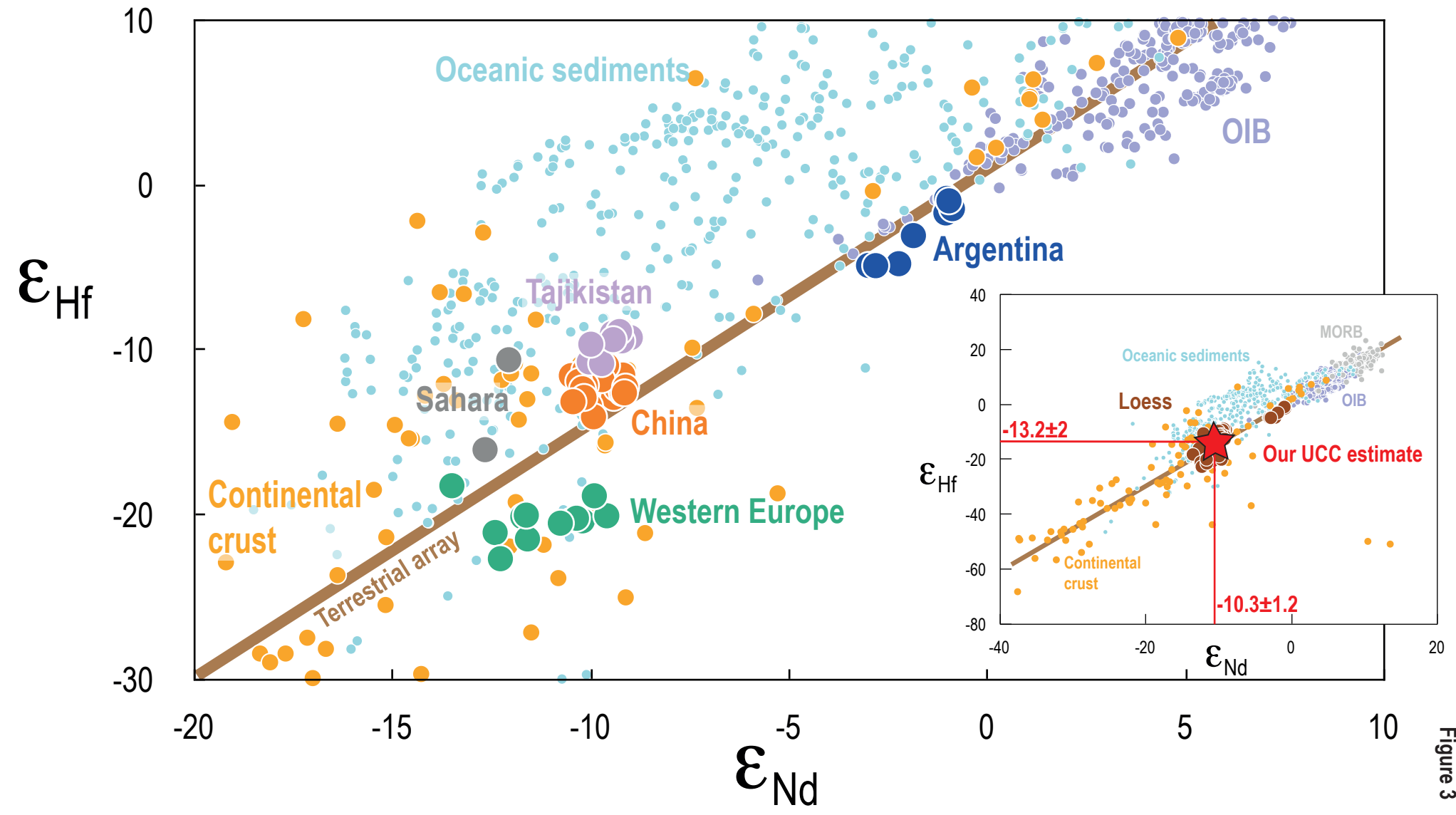


Figure 3

Figure 4

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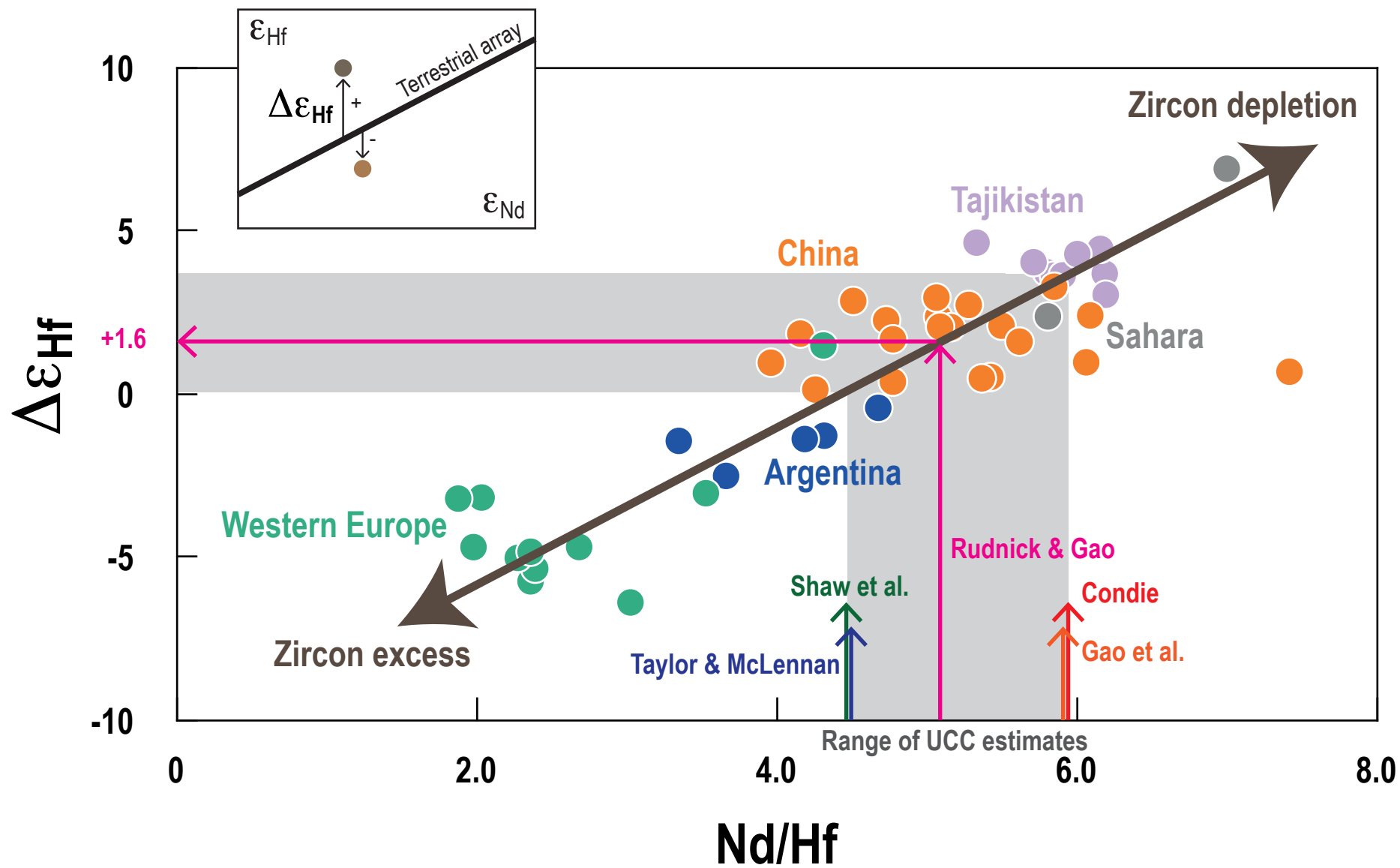


Figure 4

Figure 5  
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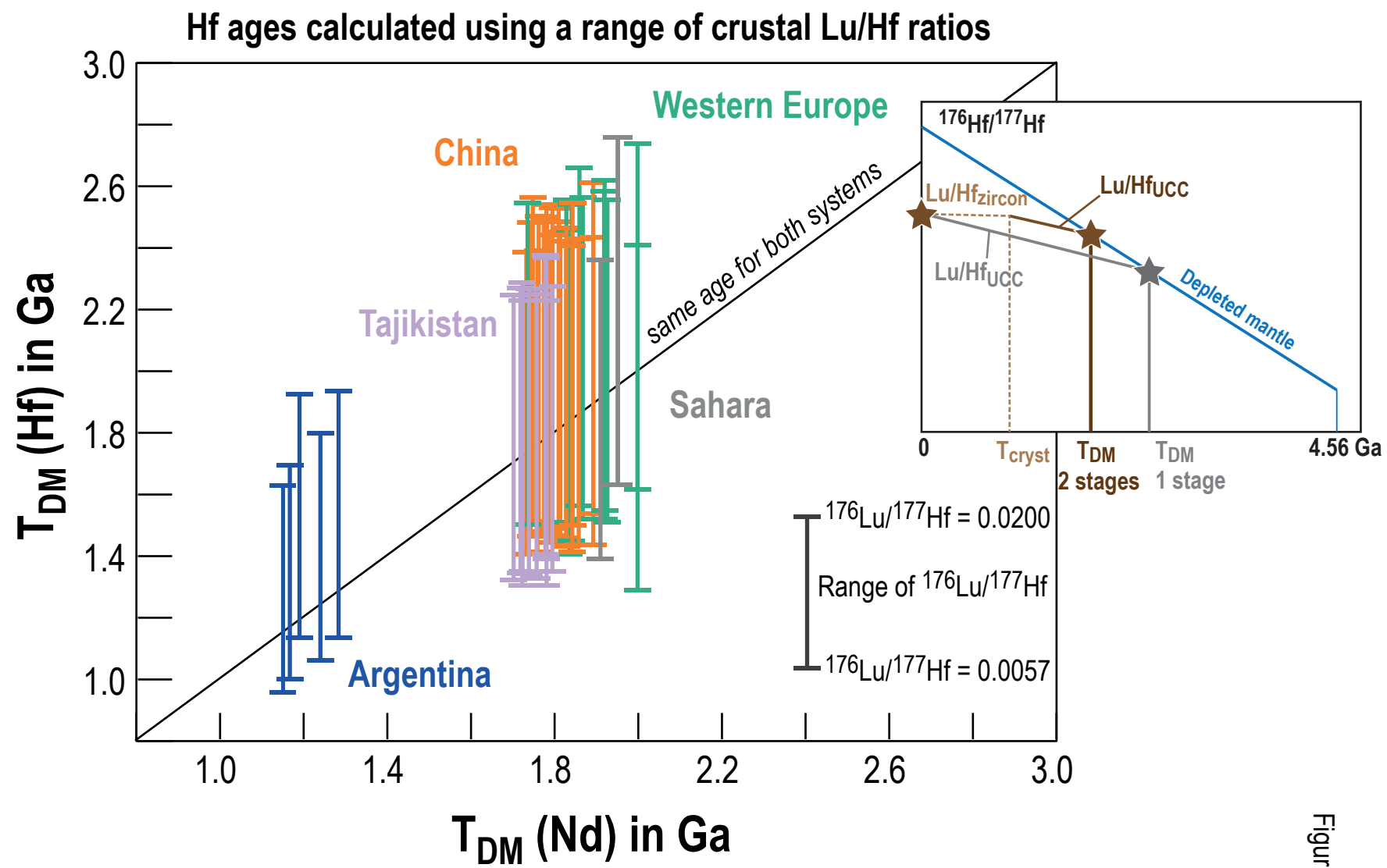


Figure 5

Figure 6

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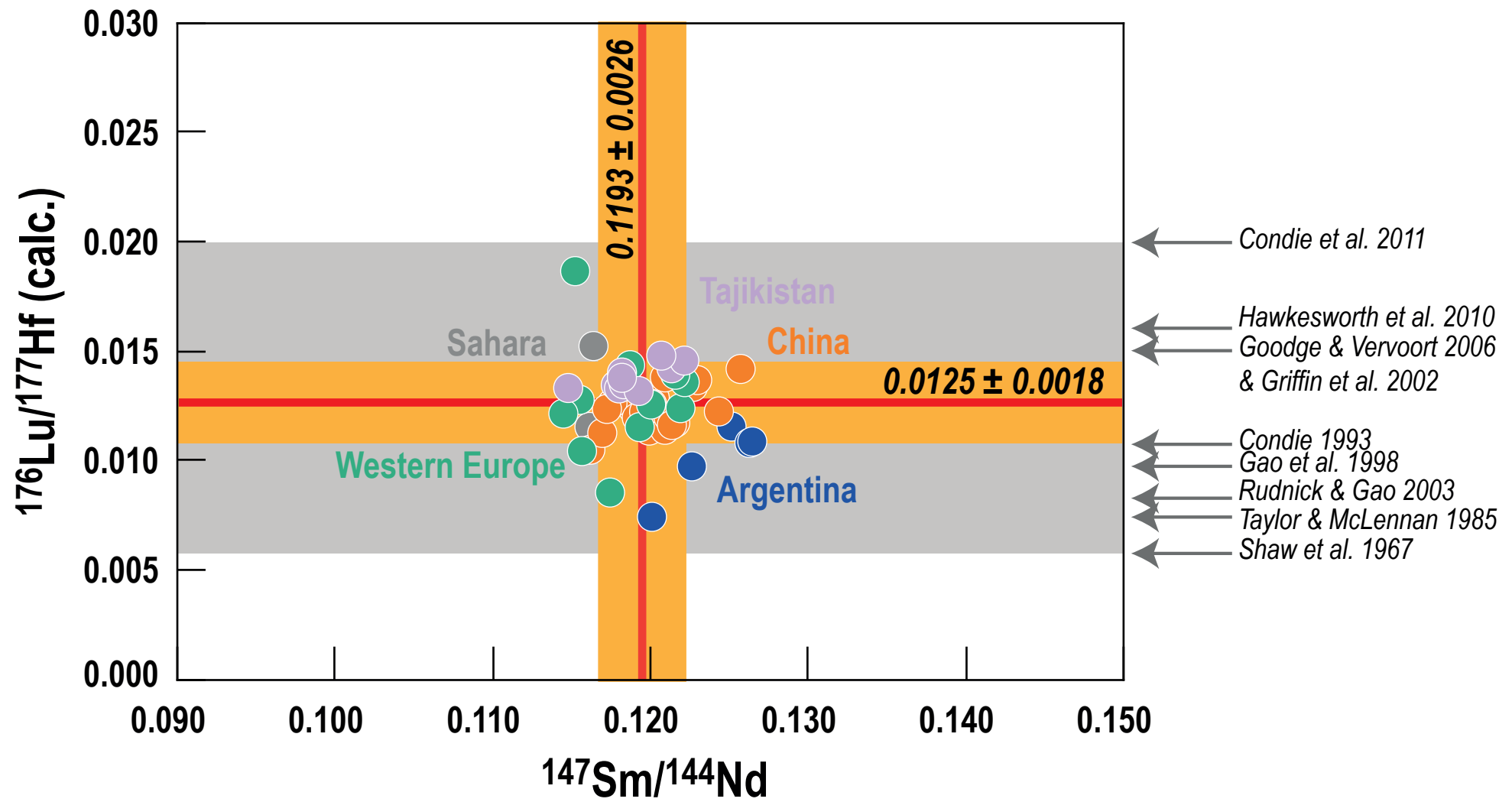


Figure 6



Table 1: Nd and Hf isotopic compositions of the loess samples

Sample	Location	$^{143}\text{Nd}/^{144}\text{Nd}$ d	2s	$\epsilon_{\text{Nd}}$	$^{147}\text{Sm}/^{144}\text{Nd}$ d	$^{176}\text{Hf}/^{177}\text{Hf}$ f	2s	$\epsilon_{\text{Hf}}$	$^{176}\text{Lu}/^{177}\text{Hf}$
<b>Western Europe</b>									
HOT1 whole rock	St Brieuc, France	<b>0.512106</b>	0.000009	<b>-10.2</b>	0.1219	<b>0.282209</b>	0.000008	<b>-20.4</b>	0.00574
HOT1 < 160 mm	St Brieuc, France	<b>0.512098</b>	0.000010	<b>-10.4</b>	0.1193	<b>0.282213</b>	0.000007	<b>-20.2</b>	0.00541
PR RT (whole rock)	Port Racine, Normandy, France	<b>0.512078</b>	0.000009	<b>-10.8</b>	0.1222	<b>0.282205</b>	0.000013	<b>-20.5</b>	0.00477
FOUG 3a<160 mm	Fougères, France	<b>0.512029</b>	0.000006	<b>-11.7</b>	0.1187	<b>0.282216</b>	0.000006	<b>-20.1</b>	0.00537
SAB 1a <160 mm	Sables d'or, France	<b>0.512138</b>	0.000009	<b>-9.6</b>	0.1174	<b>0.282218</b>	0.000015	<b>-20.1</b>	0.00613
NS 6 < 160 mm	Nantois, France	<b>0.512121</b>	0.000006	<b>-9.9</b>	0.1216	<b>0.282252</b>	0.000012	<b>-18.9</b>	0.00634
LO94	Spitsbergen (Svalbard)	<b>0.511937</b>	0.000010	<b>-13.5</b>	0.1152	<b>0.282269</b>	0.000010	<b>-18.2</b>	0.00905
P2E1	Spitsbergen (Svalbard)	<b>0.511993</b>	0.000009	<b>-12.4</b>	0.1155	<b>0.282189</b>	0.000013	<b>-21.1</b>	0.00717
K14	Kesselt, Belgium	<b>0.512000</b>	0.000011	<b>-12.3</b>	0.1200	<b>0.282144</b>	0.000006	<b>-22.7</b>	0.00509
R 11	Rocourt, Belgium	<b>0.512035</b>	0.000009	<b>-11.6</b>	0.1156	<b>0.282178</b>	0.000010	<b>-21.5</b>	0.00451
SCIL	Scilly Island, England	<b>0.512034</b>	0.000008	<b>-11.6</b>	0.1145	<b>0.282219</b>	0.000018	<b>-20.0</b>	0.00464
<b>China</b>									
JX-4	Jixian	<b>0.512110</b>	0.000008	<b>-10.1</b>	0.1203	<b>0.282442</b>	0.000011	<b>-12.1</b>	0.00987
JX-6	Jixian	<b>0.512101</b>	0.000015	<b>-10.3</b>	0.1188	<b>0.282448</b>	0.000013	<b>-11.9</b>	0.00855
JX-10	Jixian	<b>0.512115</b>	0.000009	<b>-10.0</b>	0.1162	<b>0.282406</b>	0.000011	<b>-13.4</b>	0.00843
JX-2	Jixian	<b>0.512106</b>	0.000007	<b>-10.2</b>	0.1189	<b>0.282435</b>	0.000008	<b>-12.4</b>	0.00976
XF-10	Xifeng	<b>0.512124</b>	0.000009	<b>-9.9</b>	0.1176	<b>0.282470</b>	0.000009	<b>-11.1</b>	0.01011
XF-6	Xifeng	<b>0.512131</b>	0.000011	<b>-9.7</b>	0.1201	<b>0.282451</b>	0.000013	<b>-11.8</b>	0.01010
XF-2	Xifeng	<b>0.512162</b>	0.000008	<b>-9.1</b>	0.1199	<b>0.282438</b>	0.000013	<b>-12.3</b>	0.01344
XF-4	Xifeng	<b>0.512160</b>	0.000010	<b>-9.2</b>	0.1209	<b>0.282429</b>	0.000014	<b>-12.6</b>	0.00948
XF-4 dup	Xifeng					<b>0.282443</b>	0.000008	<b>-12.1</b>	
XN-2	Xining	<b>0.512102</b>	0.000009	<b>-10.3</b>	0.1169	<b>0.282414</b>	0.000009	<b>-13.1</b>	0.01078
XN-4	Xining	<b>0.512120</b>	0.000011	<b>-9.9</b>	0.1243	<b>0.282388</b>	0.000010	<b>-14.1</b>	0.00880
XN-10	Xining	<b>0.512108</b>	0.000008	<b>-10.2</b>	0.1191	<b>0.282421</b>	0.000010	<b>-12.9</b>	0.00911
XN-6	Xining	<b>0.512094</b>	0.000008	<b>-10.5</b>	0.1196	<b>0.282413</b>	0.000008	<b>-13.1</b>	0.00835
L3	Luochuan	<b>0.512146</b>	0.000010	<b>-9.4</b>	0.1216	<b>0.282421</b>	0.000007	<b>-12.9</b>	0.01110
L4	Luochuan	<b>0.512138</b>	0.000010	<b>-9.6</b>	0.1257	<b>0.282457</b>	0.000014	<b>-11.6</b>	0.01082
L5	Luochuan	<b>0.512150</b>	0.000012	<b>-9.4</b>	0.1211	<b>0.282437</b>	0.000008	<b>-12.3</b>	0.01227
L6	Luochuan	<b>0.512158</b>	0.000009	<b>-9.2</b>	0.1213	<b>0.282429</b>	0.000005	<b>-12.6</b>	0.01114
L7	Luochuan	<b>0.512140</b>	0.000009	<b>-9.6</b>	0.1227	<b>0.282460</b>	0.000007	<b>-11.5</b>	0.01145
L7 dup	Luochuan	<b>0.512158</b>	0.000009	<b>-9.2</b>		<b>0.282459</b>	0.000009	<b>-11.5</b>	
L9	Luochuan	<b>0.512137</b>	0.000009	<b>-9.6</b>	0.1172	<b>0.282475</b>	0.000006	<b>-11.0</b>	0.01023
L1	Luochuan	<b>0.512125</b>	0.000010	<b>-9.9</b>	0.1229	<b>0.282456</b>	0.000014	<b>-11.6</b>	0.01194
L2	Luochuan	<b>0.512109</b>	0.000012	<b>-10.2</b>	0.1209	<b>0.282467</b>	0.000010	<b>-11.2</b>	0.01243
<b>Argentina</b>									
12-14	Argentina	<b>0.512515</b>	0.000009	<b>-2.2</b>	0.1201	<b>0.282650</b>	0.000005	<b>-4.8</b>	0.00821
24-26	Argentina	<b>0.512577</b>	0.000009	<b>-1.0</b>	0.1251	<b>0.282762</b>	0.000007	<b>-0.8</b>	0.01140
32RT	Argentina	<b>0.512576</b>	0.000008	<b>-1.1</b>	0.1263	<b>0.282737</b>	0.000006	<b>-1.7</b>	0.00984
32RT dup	Argentina	<b>0.512580</b>	0.000008	<b>-1.0</b>		<b>0.282758</b>	0.000006	<b>-1.0</b>	
40RT	Argentina	<b>0.512534</b>	0.000007	<b>-1.9</b>	0.1264	<b>0.282698</b>	0.000004	<b>-3.1</b>	0.00846
LUJA	Argentina	<b>0.512476</b>	0.000006	<b>-3.0</b>	0.1226	<b>0.282647</b>	0.000005	<b>-4.9</b>	0.00807
<b>Sahara</b>									
Sahara dust collected in Meylan	Meylan, France	<b>0.511980</b>	0.000007	<b>-12.7</b>	0.1161	<b>0.282331</b>	0.000008	<b>-16.1</b>	0.01020
Sahara dust collected at 2900m altitude	Alpes, France	<b>0.512011</b>	0.000007	<b>-12.1</b>	0.1164	<b>0.282485</b>	0.000005	<b>-10.6</b>	0.01220
<b>Tajikistan</b>									
TJK2772	Chashmanigar, Tajikistan	<b>0.512163</b>	0.000007	<b>-9.1</b>	0.1178	<b>0.282526</b>	0.000006	<b>-9.2</b>	0.01152
TJK2773	Chashmanigar, Tajikistan	<b>0.512168</b>	0.000011	<b>-9.0</b>	0.1213	<b>0.282523</b>	0.000005	<b>-9.3</b>	0.01206
TJK2930	Chashmanigar, Tajikistan	<b>0.512115</b>	0.000006	<b>-10.0</b>	0.1180	<b>0.282482</b>	0.000006	<b>-10.7</b>	0.01117
TJK3012	Chashmanigar, Tajikistan	<b>0.512154</b>	0.000006	<b>-9.3</b>	0.1221	<b>0.282517</b>	0.000004	<b>-9.5</b>	0.01163
TJK3070	Chashmanigar, Tajikistan	<b>0.512157</b>	0.000007	<b>-9.2</b>	0.1183	<b>0.282518</b>	0.000007	<b>-9.5</b>	0.01145
TJK3148	Chashmanigar, Tajikistan	<b>0.512145</b>	0.000006	<b>-9.5</b>	0.1207	<b>0.282530</b>	0.000006	<b>-9.0</b>	0.01189
TJK3179	Chashmanigar, Tajikistan	<b>0.512154</b>	0.000006	<b>-9.3</b>	0.1182	<b>0.282534</b>	0.000007	<b>-8.9</b>	0.01221
TJK3198	Chashmanigar, Tajikistan	<b>0.512131</b>	0.000008	<b>-9.7</b>	0.1192	<b>0.282479</b>	0.000006	<b>-10.8</b>	0.01146
TJK2814	Chashmanigar, Tajikistan	<b>0.512146</b>	0.000007	<b>-9.4</b>	0.1182	<b>0.282520</b>	0.000006	<b>-9.4</b>	0.01141
TJK3165	Chashmanigar, Tajikistan	<b>0.512117</b>	0.000009	<b>-10.0</b>	0.1148	<b>0.282512</b>	0.000007	<b>-9.7</b>	0.01056

Table2: Compilation of the parent-daughter ratios and Nd and Hf isotopic compositions of various reservoirs

Reservoir	Source	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon_{\text{Nd}}$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$\epsilon_{\text{Hf}}$	Lu (ppm)	Hf (ppm)	$^{176}\text{Lu}/^{177}\text{Hf}$
Bulk Silicate Earth	Bouvier et al. 2008	0.512630	-			0.1960	0.282785	-			0.0336
Most depleted MORB*	Chauvel et al. 2008	0.513270	12.48			0.2172	0.283381	21.08			0.0403
Depleted mantle	Salters and Stracke 2004			0.27	0.713	0.2289			0.063	0.199	0.0449
Average MORB	Chauvel et al. 2008	0.513072	8.62			0.2106	0.283208	14.96			0.0384
"	Gale et al. 2013	0.513074	8.66			0.2107	0.283000	7.6			0.0360
"	Gale et al. and Hf on terrestrial array	0.513074	8.66			0.2107	0.283199	14.63			0.0383
Source of new crust	Thiery et al. 2011 and Nd on terrestrial array	0.513027	7.74				0.283158	13.2			
<b>Upper Continental crust</b>											
	Rudnick and Gao TOG 2003			4.7	27	0.1052			0.31	5.3	0.0083
	Taylor and McLennan 1985			4.5	26	0.1046			0.32	5.8	0.0078
	Gao et al. 1998			5.09	30.4	0.1012			0.35	5.12	0.0097
	Shaw et al. 1967&1976			4.61	25.9	0.1076			0.233	5.8	0.0057
	Condie 1993			5.09	30.4	0.1012			0.32	4.3	0.0106
	Wedepohl 1995			4.7	25.9	0.1097			0.27	5.8	0.0066
	McCulloch and Wasserburg, 1978					0.1150					
	Goldstein et al. 1984					0.1150					
	Allègre and Rousseau 1984					0.1120					
	Jahn and Condie 1995					0.1180					
	Goodge and Vervoort 2006										0.0150
	Griffin et al. 2002										0.0150
	Hawkesworth et al. 2010										0.0159
	Condie et al. 2011										0.0200
<b>Our estimate for Upper Continental Crust</b>		<b>0.512101</b>	<b>-10.3</b>			<b>0.1193</b>	<b>0.282412</b>	<b>-13.2</b>			<b>0.0125</b>
<b>uncertainty at one sigma</b>		<b>±0.000060</b>	<b>±1.2</b>			<b>±0.0026</b>	<b>±0.000060</b>	<b>±2</b>			<b>±0.0018</b>

**Supplementary table**

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**Supplementary figure**

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