

1 **ESR and ESR/U-series chronology of the Middle Pleistocene site of Tourville-la-Rivière (Normandy, France) - a**  
 2 **multi-laboratory approach**

3 Jean-Jacques BAHAIN<sup>1</sup>, Mathieu DUVAL<sup>2,3</sup>, Pierre VOINCHET<sup>1</sup>, Hélène TISSOUX<sup>1,4</sup>, Christophe FALGUERES<sup>1</sup>,  
 4 Rainer GRÜN<sup>2</sup>, Davinia MORENO<sup>3</sup>, Qingfeng SHAO<sup>5</sup>, Olivier TOMBRET<sup>1</sup>, Guillaume JAMET<sup>6</sup>, Jean-Philippe  
 5 FAIVRE<sup>7</sup> & Dominique CLIQUET<sup>8</sup>

6 <sup>1</sup> UMR 7194 HNHP, Muséum National d'Histoire Naturelle, Département Homme et environnement, 1 rue René  
 7 Panhard, 75013 PARIS. [bahain@mnhn.fr](mailto:bahain@mnhn.fr), [pvoinch@mnhn.fr](mailto:pvoinch@mnhn.fr), [falguere@mnhn.fr](mailto:falguere@mnhn.fr), [olivier.tombret@mnhn.fr](mailto:olivier.tombret@mnhn.fr)

8 <sup>2</sup> Australian Research Centre for Human Evolution (ARCHE), Environmental futures Research Institute, Griffith  
 9 University, NATHAN QLD 4111, Australia. [m.duval@griffith.edu.au](mailto:m.duval@griffith.edu.au), [rainer.grun@griffith.edu.au](mailto:rainer.grun@griffith.edu.au)

10 <sup>3</sup> Geochronology, Centro Nacional de Investigación sobre la Evolución Humana (CNEIEHE), Paseo Sierra de  
 11 Atapuerca, 3, 09002 Burgos, Spain. [davinia.moreno@cenieh.es](mailto:davinia.moreno@cenieh.es)

12 <sup>4</sup> BRGM, DGR/GAT, 3 Avenue Claude Guillemin, BP 36009, 45060, Orléans, France and UMR7194 HNHP.  
 13 [h.tissoux@brgm.fr](mailto:h.tissoux@brgm.fr)

14 <sup>4</sup> Geochronology, Centro Nacional de Investigación sobre la Evolución Humana, Paseo de Atapuerca, 3, 09002  
 15 Burgos, Spain [davinia.moreno@cenieh.es](mailto:davinia.moreno@cenieh.es)

16 <sup>5</sup> Nanjing Normal University, College of Geography Science, Nanjing, China. [qingfengshao@njnu.edu.cn](mailto:qingfengshao@njnu.edu.cn)

17 <sup>6</sup> GéoArchÉon SARL, 30, rue de la Victoire, F-55210 Viéville-sous-les-Côtes, France & Laboratoire de Géographie  
 18 Physique Environnements quaternaires et actuels (UMR 8591, CNRS-Universités Paris I & Paris XII), 1 place  
 19 Aristide Briand, F-92195 Meudon cedex, France [guillaume.jamet@geoarcheon.fr](mailto:guillaume.jamet@geoarcheon.fr)

20 <sup>7</sup> Université de Bordeaux, PACEA, UMR 5199, F\_33615, Pessac Cedex, France. [jean-philippe.favre@u-bordeaux.fr](mailto:jean-philippe.favre@u-bordeaux.fr)

22 <sup>8</sup> Service Régional de l'Archéologie, Direction régionale des Affaires culturelles de Basse-Normandie, 13bis, rue  
 23 de Saint-Ouen, 14052 Caen cedex 04 & UMR CNRS 6566, Université de Rennes 1, France :  
 24 [dominique.cliquet@culture.gouv.fr](mailto:dominique.cliquet@culture.gouv.fr)

25 **Abstract** – Tourville-la-Rivière (Normandy, France) is one of the rare Middle Pleistocene palaeoanthropological  
 26 localities of Northern France. Electron Spin Resonance (ESR) and combined ESR/U-series dating methods were  
 27 independently applied by different teams on sediments and teeth from this site. The present work provides an  
 28 overview of this multi-laboratory dating work by integrating a description and discussion of the methodologies  
 29 employed and results obtained.

30 Results confirm that the ESR/U-series analyses of the teeth are greatly dependent on the U-uptake histories of  
 31 the dental tissues. Although all teeth come from the same archeological level, the samples analysed by each  
 32 team display two different patterns for the U-series data. This is most likely related to the different sampling  
 33 areas selected by each team and may be interpreted as the result of local variations in the geochemical  
 34 conditions of the surrounding environment. Concerning the ESR dating of optically bleached quartz grains, the  
 35 use of the multiple centre approach seems crucial when dating such fluvial and fluvio-lacustrine sediments. Our  
 36 results also confirm the great potential of the Ti-H centre to date late Middle Pleistocene deposits.

37 Despite some (expected) discrepancies related to the independent use of parameters and approaches by the  
 38 different teams involved in this multi-laboratory study, the whole ESR and ESR/U-series data set collected from  
 39 Tourville-la-Rivière locality consistently correlates stratigraphic levels D1 to I and associated human occupation  
 40 to MIS7.

41

42 **Keywords** – Electron Spin Resonance dating; combined ESR/U-series dating; Tourville-la-Rivière; Middle  
 43 Pleistocene; teeth; optically bleached quartz grains.

44 **1. Introduction**

45 Since the late 1980s, Electron Spin Resonance (ESR) of optically bleached quartz grains and combined ESR/U-  
46 series of fossil teeth are amongst the most employed dating applications to constrain the chronology of Middle  
47 Pleistocene archaeo-palaeontological sites. Previous cross-comparison studies showed good agreement with  
48 results derived from other numerical dating methods such as Luminescence, U-series and  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  (e.g. Duval  
49 et al., 2017; Méndez-Quintas et al., 2018; Pereira et al., 2018). Unfortunately, given the very limited number of  
50 laboratories and researchers specialized in the ESR dating applications mentioned above, inter-laboratory  
51 comparison studies remain very rare. Additionally, the material analyzed is typically quite small and  
52 heterogeneous, which does not facilitate the implementation of such large-scale comparative programs.

53 Sometimes, a given site or archaeological level has been dated with ESR or ESR/U-series methods by different  
54 teams in separate works, such as for example the sites of La Micoque (Dordogne, France) (Schwarcz and Grün,  
55 1988; Falguères et al., 1997) or Atapuerca Gran Dolina TD6 (Spain) (Falguères et al., 1999; Duval et al., 2018) or,  
56 more rarely, within the framework of a single study (e.g. Dirks et al., 2017). However, except for critical  
57 evaluations of previously published data, these studies have in most cases not led to any proper scientific  
58 discussions about the experimental conditions employed and their impact on the final age estimates.

59 Tourville-la-Rivière is one of the rare Middle Pleistocene palaeoanthropological localities of Northern France. It  
60 has recently been submitted to a series of independent dating studies by different ESR dating laboratories  
61 (CENIEH-RSES, MNHN and BRGM) involving combined ESR/U-series dating of fossil teeth (CENIEH-RSES in Faivre  
62 et al., 2014; MNHN in Bahain et al., 2015) and ESR dating of optically bleached quartz grains (MNHN and BRGM,  
63 unpublished data). The present paper aims to compile all the chronological data collected for this site in order  
64 to enable a proper comparison of the different methodologies employed (from sampling to age determination)  
65 and evaluate their impact on the age results. When necessary, new age calculations were performed in  
66 accordance to recent methodological developments. These data will contribute to refine the chronology of the  
67 different archaeological and geological levels for this key palaeoanthropological locality.

## 68 2. Tourville-La-Rivière site

69 Located on a low fossil fluvial terrace of the Seine System, close to Rouen city in Normandy (Figure 1), Tourville-  
70 la-Rivière site (Seine-Maritime, France) has been known since the late 1960s (see Lautridou, 1985 and Jamet,  
71 2015 and references therein). Several areas within the site have been successively excavated during the  
72 following fifty years, delivering an abundant late Middle Pleistocene mammal fauna (Auguste, 2009; Bemilli  
73 2010, 2014), a rich archaeological Middle Paleolithic lithic assemblage (Cliquet et al., 2010; Faivre et al., 2014)  
74 and three human arm bones attributed to an individual of the Neanderthal lineage (Faivre et al., 2014).

75

76 **Figure 1** – Location of the Tourville-la-Rivière site, Northern France, in the Seine valley terrace system (after  
77 Jamet, 2015)

78 Tourville-la-Rivière offers one of the longest Middle Pleistocene continental stratigraphic sequences (>30 m  
79 thick) in Western Europe (Lautridou, 1985) (Figure 2). At least two climatic cycles are recorded on a fluvial  
80 terrace level corresponding to the T2 terrace of the Seine system (Figure 1). The lower part of the sequence  
81 (units A-D) consists of periglacial coarse sands and gravels units with intercalations of fine-grained interglacial  
82 fluvial or estuarine sediments. The upper part (units E to J) corresponds to successions of fine-grained  
83 sediments, gravels and paleosols, covered by periglacial slope deposits (units K and L) (Lautridou, 1985 ; Jamet,  
84 2015 ; Chauhan et al., 2017). Chronological data available before 2014 (ESR on mollusk shells, Stremme, 1985;  
85 Amino acid racemization (AAR) also on mollusk shells, Ochietti et al., 1987; thermoluminescence (TL) and  
86 Infra-red stimulated luminescence (IRSL) on sediments, Balescu et al., 1997; see data in Table 2) correlated the  
87 fluvial and estuarine deposits to the Saalian stage and place the deposition of units B and D1 during MIS 9 and  
88 7, respectively.

89 The locality has recently been the subject of two successive archaeological excavation campaigns in 2008  
90 (Cliquet et al., 2010) and 2010 (Faivre et al., 2014) and a new stratigraphic study was performed within the  
91 framework of Guillaume Jamet's PhD thesis (Jamet, 2015). The latter enabled to propose that the position of  
92 the end of the MIS7 is recorded higher up in the sequence, i.e. between units E and F instead of between D1  
93 and D2 as previously proposed by Lautridou (1985) (Figure 2).

94

95 **Figure 2** – Overview of the sedimentary sequence at Tourville-la-Rivière, including stratigraphic subdivision,  
96 identified biomarkers, numerical dating results available before the recent ESR/U-series and ESR studies, and  
97 palaeoenvironmental interpretation (after Jamet, 2015)

### 98 3. Electron Spin Resonance (ESR) dating: basic principles

#### 99 a. Combined ESR/U-series dating of fossil teeth

100 The combined use of electron spin resonance (ESR) and U-series dating methods (ESR/U-series) to date  
101 Pleistocene mammal remains has been first proposed at the end of 1980s (Grün et al., 1988). The age  
102 calculation for a tooth requires the determination of two parameters: an estimate of the total dose of radiation  
103 received during its archaeological history, usually named equivalent dose ( $D_e$ ), and the dose rate ( $d_a$ ), i.e. an  
104 estimate of the dose annually absorbed by the sample. The  $D_e$  value is classically determined using a multiple  
105 aliquot additive dose (MAAD) method. The dose rate is assessed from the radioelement content of the sample  
106 itself and of the surrounding sediment, in addition to a component from the cosmic rays (see Duval, 2015 for  
107 further detail).

108 The main complication in combined ESR/U-series dating of fossil teeth is related to the uranium incorporation  
109 into dental tissues during the fossilization process. This phenomenon depends on the considered tissue, of the  
110 geological nature of the site and of its age. It requires the use of mathematical models allowing the description  
111 of the U-content evolution with time in a given tissue. The most popular one, uranium-series (US) model, has  
112 been proposed by Grün et al. (1988), who introduced a parameter ( $p$ ) to describe the U-uptake kinetics for  
113 each dental tissue. This kinetics is mathematically assessed from the ESR and present-day U-series data  
114 measured in each dental tissue. Consequently, only one combined US-ESR age fits the available dataset (see  
115 Shao et al., 2015 for the mathematical basis of the US model).

116 The US model can only be applied if the ESR age calculated assuming an early U-uptake (EU) for all the tissues  
117 of a tooth is greater than the corresponding EU-U-series ages. In other words, the occurrence of U-leaching  
118 would preclude the use of the US model, which may frequently occur in Pleistocene open air sites. More  
119 recently, Shao et al. (2012) proposed the accelerated uptake (AU) model in order to enable combined U-  
120 series/ESR age calculations in presence of uranium leaching.

121 Another alternative to the US model is the closed system uranium-series (CSUS or CSUS-ESR) model that  
122 assumes that all uranium migrated into the dental tissue at the time given by the apparent closed system U-  
123 series age (Grün 2000). On a given data set, the CSUS model typically provides a maximum possible age  
124 estimate. By using both CSUS and US models for a given sample, the resulting age range typically encompass all  
125 possible U-uptake histories (e.g. Duval et al., 2018), as long as there are no U-leaching episodes.

#### 126 b. ESR dating of optically bleached quartz grains

127 Unlike for fossil teeth, ESR dating of quartz grains is based on the evaluation of light-sensitive signals. The  
128 exposure of quartz grains to natural sunlight (an especially to UV-rays; Tissoux et al., 2007) leads to the  
129 significant decrease of the intensity associated to the ESR signal some paramagnetic centres. This  
130 phenomenon, called optical bleaching, corresponds to a drain of trapped electrons in relation to the energy  
131 received during the light exposure (Toyoda et al., 2000). Hence, the event tentatively dated here is not crystal  
132 formation, as for the speleothems, or a biological event, as for palaeontological remains, but the last exposure  
133 of the quartz grains to the sunlight before their burial into the sediment (Yokoyama et al. 1985).

134 However, the different ESR centres measured in quartz do not all show the same bleaching features. If the ESR  
135 intensity of the titanium (Ti) centres (mainly Ti-H and Ti-Li) can be fully reset, the aluminium (Al) signal cannot  
136 be zeroed instead. Its ESR intensity decreases until a plateau value corresponding to the presence in the quartz  
137 of traps that cannot be emptied by light exposure (Toyoda et al., 2000; Tissoux et al., 2012). This residual value  
138 is sample dependent: it is typically determined by exposing an aliquot of the natural sample to a UV solar  
139 simulator (e.g. Voinchet et al., 2003). The ESR intensity corresponding to the non-bleachable part of the ESR Al  
140 signals is then subtracted to the ESR signal intensity of the studied sample before any  $D_e$  determination (so-  
141 called total bleach method, Forman, 2000). The resulting  $D_e$  value corresponds to the total dose of radiation  
142 received by the sample during burial (Voinchet et al. 2004).

143 In order to evaluate the bleaching level achieved by the ESR signals during sediment transport, an approach  
144 based on the measurements of Al and Ti signals (multiple centre approach, MC) was first proposed by Toyoda  
145 et al. (2000). This MC approach aims to take advantage of the different bleaching kinetics typically observed for  
146 the Al, Ti -Li and Ti-H centres. The Ti-H signal is known to be fully reset at a much faster rate than the Ti-Li  
147 signal, while the Al signal shows a much slower bleaching kinetics in comparison (Toyoda et al., 2000; Duval et  
148 al., 2017). Incomplete bleaching would therefore lead to different burial dose estimates for these three ESR  
149 signals, with the Ti-H signal typically providing the smallest dose and the Al signal the biggest one. In this case,  
150 the first one would most likely be the closest estimate of the true burial dose absorbed by the sample, whereas  
151 the second one would provide a maximum possible estimate (see Duval et al., 2017). However, the systematic  
152 application of the MC approach is sometimes complicated by the weak ESR signal measured for the Ti-H centre  
153 (see Rixhon et al., 2017), which makes it complicated to obtain meaningful results.

154 A few recent applications studies may provide a fair idea of the time range applicability achieved by the MC  
155 approach. Ti-H signal has proven to produce age estimates consistent with independent age control from about  
156 300 ka to 40 ka (e.g., Duval et al., 2017; Kreutzer et al., 2018), while Ti-Li and Al centres may provide accurate  
157 age results between about 200 ka and 2 Ma (Beerten and Stesman, 2006; Mendez-Quintas et al., 2018;  
158 Sahnouni et al. 2018; Voinchet et al., this issue). For a time period younger than about 40 ka, none of the Al and  
159 Ti centres seem to yield accurate age results (e.g., Mendez-Quintas et al., 2018), which indicate the difficulty to  
160 detect low dose estimates (<100 Gy) with these signals. Finally, one may not exclude that the lower dating limit  
161 of the ESR method may well be beyond 2 Ma, as suggested in first instance by the few existing thermal stability  
162 studies (see an overview in Toyoda, 2015). However, it is still unclear whether these laboratory estimates are  
163 accurate given the uncertainty involved in the evaluation process and the impossibility to reproduce natural  
164 condition during annealing experiments.

165

#### 166 4. Material and methods

##### 167 4.1. Combined ESR/U-series dating of fossil teeth

168 Eight fossil teeth from the 2010 excavation (Figure 3) were analyzed by the CENIEH-RSES (Centro Nacional de  
169 Investigación sobre la Evolución Humana, Spain – Research School of Earth Sciences, Australian National  
170 University, Australia) team (see details in Faivre et al., 2014): five of them were found in the lower part of Layer  
171 D2 (T1, T2, T4, T5 and T8) and three in the upper part (T3, T6 and T7). Four sediment samples were collected  
172 from Layer D2, with three in direct contact with T4, T5 and T7. They were used to derive the external beta and  
173 gamma dose rate values. Since the dating analyses started at the end of 2011, i.e. more than one year after the  
174 end of the excavation (September 2010), the excavation site could no longer be accessed to carry out *in situ*  
175 gamma dose rate measurements.

176

#### 177 **Figure 3** – Sampling location of the analyzed teeth and sediments from the Tourville-la-Rivière site

178 Six horse teeth from the D2 level excavated in 2008 and associated sediments (Figure 3) have been analyzed by  
179 the MNHN (Muséum National d'Histoire Naturelle, France) team following the experimental protocol described  
180 in Bahain et al. (2012). *In situ* gamma dose rate evaluation was also performed in 2011 on an outcrop  
181 connecting the two main excavation areas. Four measurements were performed within D2 layer in order to  
182 evaluate lateral variations of radioactivity.

183 The analytical protocols followed by the two teams are summarized in Table 1. They are quite similar for the  
184 sample preparation and  $D_e$  determination, but differ for the U-series analyses and some of the ESR parameters  
185 used in the age calculation. The main differences may be summarized as follows: (i) external dose rate was  
186 determined from laboratory analyses of sediment only for CENIEH-RSES tooth samples, while gamma dose rate  
187 of the MNHN samples was derived from *in situ* measurements ; (ii) Potential Rn losses from the dental tissues  
188 was evaluated for the MNHN samples, while equilibrium was assumed for the CENIEH-RSES teeth; (iii) the  
189 cosmic dose rate was estimated from the present-day depth by CENIEH-RSES team (i.e. 21m, leading to a  
190 cosmic dose of 26.8  $\mu\text{Gy/a}$ ), while MNHN used a geological model based on the sediment deposition  
191 interpretation from Jamet (2015) (leading to a mean cosmic dose of about 100 $\mu\text{Gy}$ ); (iv) the dose rate

192 conversion factors from Adamiec and Aitken (1998) and Guérin et al. (2011) were used by MNHN and CENIEH-  
 193 RSES teams, respectively; (v) DATA (CENIEH-RSES)(Grün, 2009) and USESR (MNHN)(Shao et al., 2015) combined  
 194 ESR/U-series age calculation programs were employed.

195

196 Table 1 – Comparison of the analytical procedures used by the CENIEH-RSES and MNHN teams for the  
 197 combined U-series/ESR dating of fossil teeth.

198

#### 199 4.2. ESR dating of quartz grains

200 Six sediment samples were collected in 2011 at Tourville-la-Rivière, two from the D1 level (Tourville 5 & 6) and  
 201 another four from the D2 level (Tourville 1 to 4). These last four samples actually correspond to the *in situ*  
 202 gamma measurement points used for the MNHN teeth (Figure 3). *In situ* gamma measurements were  
 203 systematically performed at each sampling point using an Inspector1000 Canberra gamma spectrometer.  
 204 Gamma dose rate were obtained using the threshold approach. By this approach, the count-rate of the  
 205 spectrometer, proportional to the gamma dose-rate, is directly determined independently of the  
 206 radioelements sources (U, Th, K) (see details in Mercier & Falguères, 2007).

207

208 Four sediment samples were collected by the BRGM (Bureau de Recherche Géologique et Minière, France)  
 209 team in 2013 (TVL1301 to 04) from one new section cleaned and studied by Guillaume Jamet during his PhD  
 210 (Figure 4), located approximately 150m ESE from the MNHN sampling section (Figure 3). One sample was taken  
 211 from the D1 level (TVL1304) and the other three from I level. Here again, *in situ* gamma spectrometry  
 212 measurements were systematically performed using an Ortec Digidart LF gamma spectrometer and gamma  
 213 dose rates derived from the Threshold approach.

214

215

216 **Figure 4** – Sampling location of the 2013 sediments from Tourville-la Rivière analyzed by the BRGM team.

217 The two teams employed the same preparation and measurement procedure. Quartz grains were extracted  
 218 using physical and chemical preparation techniques described in Voinchet et al. (2004). Aliquots were  
 219 irradiated using a panoramic <sup>60</sup>Co source (Dolo et al., 1996) with 1.25 MeV gamma rays and a dose rate of  
 220 200Gy/h. Applied irradiation dose values range from 260 to 12,000 Gy.

221 ESR measurements were performed on 100-200 µm quartz grains. The MNHN team measured the Al signal only  
 222 in all the quartz samples, whereas the BRGM applied the MC approach on two of the four samples analysed  
 223 (TVL1302 and TVL1304). The residual (non-bleachable) part of the Al signal was determined after exposing the  
 224 samples to UV light in a Dr Hönhle SOL2 solar simulator for about 1600 hrs. The light intensity received by each  
 225 artificially bleached samples was comprised between 3.2 et 3.4.10<sup>5</sup> Lux. ESR measurements were performed at  
 226 107 K with an EMX Bruker ESR X-band spectrometer using the experimental conditions outlined by Voinchet et  
 227 al., (2004). Al-signal intensities were measured from the top of the first peak of the hyperfine structure of the  
 228 quartz ESR spectra at  $g = 2.018$  and the bottom of the 16<sup>th</sup> peak at  $g = 2.002$  (Toyoda & Falguères, 2003).

229 The Ti-Li centre intensity was measured from the bottom of the peak at  $g = 1.913$  to the baseline (so called  
 230 option D in Duval and Guilarte, 2015) and the Ti-H centre signal intensity from the bottom of the doublet at  $g =$   
 231  $1.915$  to the baseline (so called option C in Duval and Guilarte, 2015). For each centre, the average and the  
 232 standard deviation of three repeated measurements were calculated and used for  $D_e$  determination.

233 Dose response curves (DRCs) were obtained by fitting an exponential+linear equation (E+L) function through  
 234 the experimental data points (Duval, 2012; Cordier et al., 2012). Fitting was performed using Microcal  
 235 OriginPro 8, with data weighted by the inverse of the square intensities.

236 The analytical protocols used by the two teams are compared in Table 2. Sample preparation, dose rate  
 237 evaluation and age calculation are strictly similar for the two procedures. Both teams used measured water  
 238 content for dose rate evaluation. The main differences concern: (i) the use of the MC approach by BRGM team;  
 239 (ii) the maximal dose of irradiation ( $D_{max}$ ) employed by each team (9,870 Gy for MNHN vs 11,700 Gy for  
 240 BRGM); (iii) the water content considered for the age calculation(5-8% for MNHN and 10-12% for BRGM,  
 241 which is most likely the result of different weather conditions before and during sampling).

242

243 **Table 2** – Comparison of the analytical protocols used by the MNHN and BRGM teams for the ESR dating of the  
 244 Tourville sediments.

245

246 **5. Results**247 *5.1. Combined ESR/U-series age estimates on teeth*248 *5.1.1. CENIEH-RSES*

249 A summary of the analytical data and results obtained by the CENIEH-RSES team is given in in Table 3. Three of  
250 the teeth from lower D2 (T4, T5 and T8) show the highest apparent U-series ages, which precluded any  
251 combined US-ESR age calculation for these samples. In contrast, the tooth samples from the upper D2 show a  
252 somewhat distinct pattern. The cement tissues of samples T6 and T7 have apparent U-series ages that are  
253 significantly older than the other tissues, which again precluded a straightforward US-ESR calculation. In  
254 summary, combined US-ESR age calculation was possible for only 3 of the 8 teeth (see also Faivre et al., 2014).  
255 All resulting age estimates are within the one-sigma error range. They are between ~174 ka and ~208 ka for  
256 teeth T1, T2 (both from lower D2) and T3 from the upper part of D2. The limited age scatter (relative standard  
257 deviation of about 9%) may be partially explained by some lateral variations in the sediment radioactivity: the  
258 external dose rate derived from the different sediment samples collected within D2 varies by about 4%.

259 Interestingly, the CSUS-ESR estimates are somewhat older but nevertheless consistent with the standard US-  
260 ESR ages, indicating thus that the U-uptake modelling has a very limited impact on the final age results. They  
261 vary between  $188 \pm 21$  and  $236 \pm 29$  ka (Table 3). Based on the weighted mean US-ESR and CSUS-ESR ages, the  
262 best age range estimate for the teeth derives from the error range given by both models, i.e. 183 to 226 ka,  
263 which represents the middle part of MIS 7 to the beginning of MIS 6.

264

265 **Table 3:** U-series and ESR data obtained by the CENIEH-RSES team (modified from Faivre et al., 2014)

266

267 *5.1.2. MNHN*

268 Although the combined US-ESR age results obtained by the MNHN team have been published earlier in Bahain  
269 et al. (2015), the data obtained were not fully given and will therefore be detailed in the present paper (Table  
270 4).

271 Contrary to the earlier dating study by Faivre et al (2014), the use of the US model for the age calculation was  
272 possible for all the teeth, indicating more homogeneous U-uptake behaviours and no occurrence of uranium  
273 leaching. The teeth analyzed by the MNHN team display relatively similar paleodosimetric parameters: the  $D_e$   
274 dispersion is low (from  $191 \pm 6$  to  $220 \pm 2$  Gy, around 6%; Table 4); the p parameters describe early uptake (p  
275 values between -0.93 and -0.69, Table 4) for all the tissues; the external environmental dose rate measured *in*  
276 *situ* within the D2 layer shows a very limited lateral variability (5%), demonstrating thus the homogeneity of the  
277 sedimentary environment (a mean value of  $417 \pm 21$   $\mu\text{Gy/a}$  was used for the age calculation). Hence, the age  
278 results obtained for the six teeth show relatively little scatter, i.e. between  $203 \pm 13$  ka and  $249 \pm 15$  ka. A mean  
279 age of  $224 \pm 11$  ka could be calculated using IsoPlot 3.0 software (Ludwig, 2003) for the D2 level, unequivocally  
280 placing the deposition of this layer during MIS7, and probably during the first part of this stage. A consistent  
281 CSUS-ESR weighted mean age of  $241 \pm 11$  ka was obtained, indicating that the U-uptake modelling has a very  
282 limited impact on the final age result, similarly to the other dating results obtained by Faivre et al (2014).

283

284 **Table 4** - U-series and ESR data obtained by the MNHN team. Analytical uncertainties are given at the one-  
285 sigma level. \* The depth was estimated from the chronostratigraphic interpretation of Jamet (2015).

286

287 *5.2. ESR on optically bleached quartz grains*288 *5.2.1. MNHN*

289 The radioelement contents, ESR ages and associated dose rate contributions determined for the Tourville-la-  
290 Rivière D1 and D2 sediments at MNHN are displayed in Table 5.

291 **Table 5**– Radioelement contents, equivalent doses, bleaching rate, dose rate contributions and ESR ages  
292 obtained for the sediments of the Tourville-la-Rivière D1 and D2 levels dated by the MNHN team. The  
293 bleaching coefficient represents the relative difference between the ESR intensities of the natural and bleached  
294 aliquots. Analytical uncertainties are given at the one-sigma level.  
295

296 Even if bleaching coefficients vary within narrow range for the whole set of samples from D2 (from 42 to 51%;  
297 Table 5), the equivalent dose values differ by a factor of 2.6, while the dose rate are all around 1100-1200  
298  $\mu\text{Gy/a}$ . Consequently, the resulting ESR ages significantly vary, from  $349 \pm 30$  to  $906 \pm 70$  ka. In comparison,  
299 the two ESR ages obtained for the D1 level show a limited scatter, with values ranging from  $334 \pm 90$  to  $390 \pm$   
300  $60$  ka. This difference between the two levels is probably related with the deposition environment: D1 level is  
301 made of coarser sediments than D2, indicating a deposition along the river bank rather than in the floodplain  
302 in high water periods. This may explain why bleaching appears to be more homogeneous among D1 samples  
303 compared with D2. Following the principles of the MC approach, all these ESR age results obtained from the  
304 measurement of the Al centre only should in first instance be interpreted as maximum possible burial age  
305 estimates for D1 and D2 levels.

### 306 5.2.2. BRGM

307 The results obtained for the samples processed by the BRGM team are displayed in Table 6. The MC approach  
308 was employed for two samples (TVL-1302 and TVL-1304) while only the Al-signal was measured for the two  
309 other samples.  
310

311 **Table 11** – Radioelement contents, equivalent doses, bleaching rate, dose rates contributions and ESR ages  
312 obtained for the sediments of the Tourville-la-Rivière D1 and I levels analyzed by the BRGM team. Analytical  
313 uncertainties are given at the one-sigma.  
314

315 In the D1 level, bleaching coefficients of the Al centre determined by the BRGM team are close to those  
316 obtained by the MNHN one (42 vs. 46%). Similarly, the total dose rate values are slightly lower but nevertheless  
317 consistent at a one-sigma level. In particular, the *in situ* gamma dose rate of TVL-1304 is the same as the dose  
318 measured by MNHN team in this level (samples Tourville 5 and 6; Table 5). Interestingly, both Al and Ti-Li ESR  
319 ages are in close agreement around 980-990 ka, and both significantly older than the results derived from  
320 MNHN samples of the same level ( $334 \pm 90$  &  $390 \pm 60$  ka; Table 4). In contrast, Ti-H signal provides a  
321 significantly younger age of  $243 \pm 14$  ka. Following the principles of the MC approach, these age differences  
322 between Al, Ti-Li and Ti-H centres may simply reflect an incomplete bleaching of the former two signals during  
323 sediment transport. Consequently, the Ti-H age result is interpreted as being the closest estimate to the true  
324 burial age of the sample. This age is actually highly consistent with those derived from the teeth of level D2  
325 above (Tables 3 & 4).

326 In contrast, the three samples from level I display very close total dose rate values (around 500-550  $\mu\text{Gy/a}$ ) and  
327 highly scattered  $D_e$  estimates from the Al centre ranging from  $187 \pm 73$  Gy to  $737 \pm 178$  Gy. As a consequence,  
328 The Al ESR ages vary from  $535 \pm 22$  to  $1354 \pm 283$  ka. The Ti-Li signal measured in sample TVL-1302 displays a  
329 significantly younger age estimate (by about 44 %) compared with that of the Al signal. Similarly, the Ti-H signal  
330 produced an even younger result (-27% compared with Ti-Li). This pattern is comparable to that observed for  
331 TVL-1304: it suggests an incomplete reset of both the Al and Ti-Li signals prior to sediment burial. In accordance  
332 with the MC approach, the Ti-H signal most likely provides the closest estimate ( $236 \pm 49$  ka) to the true burial  
333 age for this sample.

334 Samples TVL-1304 (level D1) and TVL-1302 (level I) are located at the bottom and top of the local sequence,  
335 respectively, and bracket the human occupation from level D2. They provide very close Ti-H ESR age results  
336 ( $243 \pm 14$  vs.  $236 \pm 49$  ka). As consequence, no apparent stratigraphic pattern is observed. This may be  
337 interpreted in first instance as an evidence of relatively rapid sedimentation from level D1 to D2. These results  
338 allow the correlation of the D1 to I levels to MIS7.

## 339 6. Discussion

340 The two sets of ESR and U-series data obtained on fossil teeth by the two independent teams involved in the  
341 Tourville study are overall in good agreement (Figure 5). However, the CENIEH-RSES samples displays more  
342 scattered  $D_e$  (Figure 5A) and U-series (Figure 5B) data than MNHN, while uranium concentration values in  
343 dental tissues overall vary within the same range (Figure 5C).

344

345 **Figure 5** – ESR/U-series data obtained on the Tourville-la Rivière teeth analyzed by the CENIEH-RSES and MNHN  
346 teams. A) Equivalent dose values; B) U-series data; C) U-content of the dental tissues; D) ESR/U-series (US and  
347 CSUS) and corresponding age density probability plots.

348 We can observe in particular that a majority of the CENIEH-RSES teeth recovered during the 2010 excavation  
349 are close or beyond of the U-series applicability domain, preventing the use of US model for these teeth (Figure  
350 5B). The overall smaller  $D_e$  values obtained for most of the teeth (Figure 5A) also constitute an additional  
351 limiting factor, which explains why US-ESR ages could only be calculated for three teeth. In comparison, the  
352 MNHN teeth recovered during the 2008 excavation provide more homogeneous ESR and U-series data and  
353 seem to have experienced relatively simple (and relatively early) U-uptake histories, with p-values ranging  
354 between -1 and -0.7. In contrast, CENIEH-RSES have apparently experienced more complex U-uptake, including  
355 U-leaching. This difference could be correlated to the origin of the teeth, with one excavation area (2008) that  
356 underwent more favorable geochemical conditions from an ESR dating perspective in comparison with the  
357 other (2010 area). This hypothesis is supported by the fact that two of the three CENIEH-RSES teeth that could  
358 be dated are spatially located the closest to the 2008 excavation area (Figure 3).

359 The MNHN tooth samples yield a weighted mean US-ESR and CSUS-ESR age of  $224 \pm 11$  ka and  $241 \pm 11$  ka,  
360 respectively. CENIEH-RSES results are both ~14% lower with  $194 \pm 11$  ka and  $211 \pm 15$  ka for the US and CSUS  
361 models, respectively. Nevertheless, both data sets overall at a two-sigma confidence level, supporting thus  
362 their consistency. Consequently, US-ESR and CS-US-ESR weighted mean ages of  $218 \pm 16$  ka and  $236 \pm 16$  ka  
363 may be calculated, respectively (Figure 5D). These results permit to unambiguously correlate the human  
364 occupation of the D2 level to MIS 7.

365 Although both independent data sets are consistent, we acknowledge that there may be a systematic  
366 component in the uncertainty due to differences in the analytical procedures, which might partly explain this  
367 overall 14% age underestimation of the CENIEH-RSES vs MNHN age results. This age underestimation may be  
368 the result of either a  $D_e$  underestimation or a dose rate overestimation, or possibly a combination of both.

369 For example, the impact of the absence of *in situ* gamma dose rate evaluation for the CENIEH-RSES samples can  
370 hardly be evaluated. If the impact of the water contents used for age calculations is low (less than 2%) for both  
371 dental tissues and sediment, it could be envisaged in first instance that a somewhat overestimated gamma  
372 dose rate has been derived from the laboratory analysis of unrepresentative (at a gamma-ray scale) sediment  
373 samples. However, the gamma+cosmic dose rate estimated for 2/3 CENIEH-RSES samples are already  
374 significantly lower than those obtained for the MNHN samples, mainly in relation to the cosmic dose rate used  
375 for the age calculation ( $26.8 \mu\text{Gy/a}$  for the CENIEH-RSES samples vs  $100 \mu\text{Gy/a}$  for the MNHN ones).  
376 Consequently, an additional overestimation of this parameter may be considered as unlikely.

377 The impact of using different dose rate conversion factors (Adamiec and Aitken (1998) and Guérin et al. (2011)  
378 for MNHN and CENIEH-RSES, respectively) is typically estimated to be <1% (e.g., Liritzis et al., 2013), and can  
379 therefore here considered to be negligible. Finally, any bias induced by the use of different combined ESR/U-  
380 series age calculation programs is also to be negligible (< 1%), as shown earlier in the comparison study by Shao  
381 et al. (2014).

382 Additionally, the  $D_e$  values initially considered by Faivre et al (2014) and Bahain et al. (2015) have been  
383 recalculated based on the more recent work by Duval and Grün (2016) for the selection of the maximum  
384 applied dose ( $D_{\text{max}}$ ) in order to avoid  $D_e$  overestimation. Based on their recommendations, and given the  
385 magnitude of the  $D_e$  values (between 100 and 250 Gy), the  $D_{\text{max}}/D_e$  ratio should be somewhere of between 5  
386 and 10, whereas it is ranging from 20 to 41 for the previously published data (see Table 7). Consequently, new  
387 fittings were performed with the same program (Origin), function (SSE), data weighing option ( $1/I^2$ ) and the  
388 appropriate  $D_{\text{max}}/D_e$  ratio. The resulting  $D_e$  values remain all within error, although a slight mean decrease of  
389 about 3% of about 6% may be observed for the CENIEH-RSES and MNHN data sets, respectively. One may note



390 that the errors on the revised  $D_e$  values are overall higher than those obtained earlier, which is simply the result  
391 of a fitting performed with a more reduced number of experimental data points (6-8 instead of 10 previously).  
392 In summary, the use of a smaller  $D_{max}$  value has a very limited impact on the corrected  $D_e$  value for most of the  
393 teeth, and is most likely not the main reason for the overall age difference of ~14% between the two data sets.

394 In fact, most of this age difference probably comes from the consideration of radon loss from dental tissues by  
395 the MNHN team, while a radioactive equilibrium was assumed by the CENIEH-RSES team. The Rn loss measured  
396 on both dentine and enamel of the MNHN teeth is quite important for the most of the analyzed tissues  
397 ( $^{222}\text{Rn}/^{230}\text{Th}$  ratio ranging from 0.247 to 0.523, except for two tissues showing equilibrium, Table 4). If  
398 equilibrium was assumed for these tissues, this would lead to a decrease of the age estimates ranging from -  
399 20.7 to -5.8% depending on the samples considered. Moreover, it would no longer be possible to use the US  
400 model for two samples (TVL 160 and TVL 923).

401 Lastly, if the MNHN ages are recalculated using the CENIEH-RSES parameters (conversion factors from Guérin  
402 et al.(2011) same water contents of dental tissues and sediments, Rn equilibrium, cosmic dose corresponding  
403 to a 21 m-depth, gamma dose calculated from the sediment contents), the age estimates decrease for four  
404 samples (-12.0 to -13.8 %) and increase for two of them (+1.2 to +8.0 %) leading to a reduced mean age  
405 difference of -7.8% between the two sets of samples.

406

407 **Table 7** – Comparison of the equivalent dose values obtained with or without use of the recommendations by  
408 Duval and Grün (2016).  
409

410 Concerning ESR dating of quartz, all the Al and Ti-Li ESR ages look strongly overestimated (in perhaps a lesser  
411 extent for the Ti-Li) compared with the existing chronological framework, the combined ESR/U-series ages and  
412 Ti-H ESR ages (Figure 6). In accordance with the principles of the MC approach, this overestimation is most  
413 likely due to incomplete bleaching (Duval et al., 2017). The geological nature of the D2 sediment (silty clayey  
414 deposits) could indicate a turbid water deposit in a decantation environment such as floodplain or muddy  
415 supratidal area. It could explain the age overestimate for Al and Ti-Li centres in this level (see also Voinchet et  
416 al., 2015). A similar hypothesis can be made for sandy levels D1 and I. The fluvio-estuarine origin of the  
417 sediments seems to constitute an unfavorable environment to completely reset the Al and Ti-Li signals.

418 In comparison, given its bleaching kinetics, Ti-H centre is by definition most likely to have been fully reset  
419 during sediment transport. Ti-H ESR results ( $243 \pm 14$  ka and  $236 \pm 49$  ka for units D1 and I respectively) in close  
420 agreement with the US-ESR ages obtained on fossil teeth (weighted mean age of  $218 \pm 16$  ka). All together,  
421 these data consistently date the deposition of the Tourville D1 to I units to the first part of MIS 7 rather than to  
422 the end of this interglacial stage as previously considered (Lautridou, 1985; Balescu et al., 1997). These results  
423 demonstrate the importance of using the MC approach in ESR dating of optically bleached quartz grains, which  
424 is the only way to evaluate potential incomplete bleaching of Al and Ti centres prior to burial.

425

426 **Figure 6** – ESR ages obtained on the Tourville-la Rivière sediments analyzed by the MNHN and BRGM teams  
427 using different quartz ESR centres. The grey band corresponds to the MIS 7 time range.

428

## 429 7. Conclusion

430 Tourville-la-Rivière is one of the very few Pleistocene localities where successive and independent ESR and  
431 ESR/U-series dating studies have been performed by different teams. The ESR and U-series analyses of fossil  
432 teeth show two different populations of samples with different characteristics: the MNHN samples from the  
433 2008 excavation are display homogeneous ESR and U-series data and seem to have experienced relatively  
434 simple U-uptake histories, while the scattered results obtained on CENIEH-RSES teeth (2010 excavation area)  
435 indicate a more complex evolution, including uranium leaching processes. Despite some differences in the  
436 analytical protocols independently used by each team, combined ESR/U-series age results consistently position  
437 the palaeontological remains and lithic series of D2 layer within MIS7.

438 Concerning the ESR dating of optically bleached quartz grains, the two studies performed by the MNHN and  
 439 BRGM teams show clearly that the sedimentary environments from the clayey unit D2, and the sandy units D1  
 440 and I, were simply not suitable to completely reset the ESR signals of the Al and Ti-Li centres. In contrast, the Ti-  
 441 H centre provides age estimates that are in agreement with the ESR/U-series results. This demonstrates the  
 442 great potential of this centre to date late Middle Pleistocene deposits, which is consistent with previous  
 443 observations by Duval et al. (2017). A multiple centre approach seems therefore indispensable when dating this  
 444 type of fluvio-estuarine sediment, even when the sedimentological characteristics of the sediments seem  
 445 initially quite suitable for an ESR study (as it was the case for the Tourville D1 and I units). Similar observations  
 446 have been recently made on fluvial deposits from Spain (Duval et al., 2017; Méndez-Quintas et al., 2018), Italy  
 447 (Pereira et al., 2015, 2018; Voinchet et al., this issue) or France (Duval et al., submitted).

448 Despite some (expected) discrepancies related to the independent use of parameters and approaches by the  
 449 different teams involved in this multi-laboratory study, the whole set of ESR and ESR/U-series data collected at  
 450 Tourville-la-Rivière locality consistently correlates stratigraphic levels D1 to I and associated human occupation  
 451 to MIS7.

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631

632 **Figure caption**

633 Figure 1 – Location of the Tourville-la-Rivière site, Northern France, in the Seine valley terrace system (after  
 634 Jamet, 2015)

635 Figure 2 – Overview of the sedimentary sequence at Tourville-la-Rivière, including stratigraphic subdivision,  
 636 biomarkers identified, numerical dating results available before the recent ESR/U-series and ESR studies, and  
 637 palaeoenvironmental interpretation (after Jamet, 2015)

638 Figure 3 – Sampling location or the analyzed teeth and sediments from the Tourville-la-Rivière site

639 Figure 4 – Sampling location of the 2013 sediments from Tourville-la Rivière analyzed by the BRGM team.

640 Figure 5 – ESR/U-series data obtained on the Tourville-la Rivière teeth analyzed by the CENIEH-RSES and MNHN  
641 teams. A) Equivalent dose values; B) U-series data; C) U-content of the dental tissues; D) ESR/U-series (US and  
642 CS-US) and corresponding age density probability plots.

643 Figure 6 – ESR ages obtained on the Tourville-la Rivière sediments analyzed by the MNHN and BRGM teams  
644 using different ESR centres. The grey band corresponds to the MIS 7 time range.

645

646 **Table caption**

647 Table 1 – Comparison of the analytical procedures used by the CENIEH-RSES and MNHN teams for the  
648 combined U-series/ESR dating of fossil teeth.

649 Table 2 – Comparison of the analytical protocols used by the MNHN and BRGM teams for the ESR dating of the  
650 Tourville sediments.

651 Table 3: U-series and ESR data obtained by the CENIEH-RSES team (modified from Faivre et al., 2014).

652 Table 4 - U-series and ESR data obtained by the MNHN team. Analytical uncertainties are given with  $\pm 1\sigma$ . \* The  
653 depth was estimated from the chronostratigraphic interpretation of Jamet (2015).

654 Table 5– Radioelement contents, equivalent doses, bleaching rate, dose rate contributions and ESR ages  
655 obtained for the sediments of the Tourville-la-Rivière D1 and D2 levels dated by the MNHN team. The  
656 bleaching coefficient represents the relative difference between the ESR intensities of the natural and bleached  
657 aliquots. Analytical uncertainties are given with  $\pm 1\sigma$ .

658 Table 6 – Radioelement contents, equivalent doses, bleaching rate, dose rates contributions and ESR ages  
659 obtained for the sediments of the Tourville-la-Rivière D1 and I levels analyzed by the BRGM team. Analytical  
660 uncertainties are given with  $\pm 1\sigma$ .

661 Table 7 – Comparison of the equivalent dose values obtained with or without use of Duval and Grün (2016)'s  
662 recommendations.

663

Sample	Tissue	U (ppm)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{238}\text{U}$	Apparent U-series age (ka)	Initial enamel Thickness ( $\mu\text{m}$ )	Removed thickness ( $\mu\text{m}$ )	Depth (m)	Sediment radioelement contents			$D_E$ (Gy)
									U (ppm)	Th (ppm)	K (%)	
T1	enamel	0.39 $\pm 0.00$	1.2266 $\pm 0.0483$	0.6211 $\pm 0.0331$	75.1	1160	(1): 100 $\pm$ 10	21	1.11	4.09	0.67	121
	dentine	19.68 $\pm 0.12$	1.2366 $\pm 0.0127$	0.7922 $\pm 0.0471$	106.8	$\pm 116$	(2): 110 $\pm$ 11	$\pm 3$	$\pm 0.02$	$\pm 0.02$	$\pm 0.02$	$\pm 2$
T2	enamel	0.53 $\pm 0.02$	1.2110 $\pm 0.0882$	1.0357 $\pm 0.1012$	189.0	1010	(1): 110 $\pm$ 11	21	1.11	4.09	0.67	175
	dentine	28.49 $\pm 0.97$	1.3172 $\pm 0.0032$	1.0415 $\pm 0.0103$	154.0	$\pm 101$	(2): 100 $\pm$ 10	$\pm 3$	$\pm 0.02$	$\pm 0.02$	$\pm 0.02$	$\pm 2$
T3	enamel	0.42 $\pm 0.11$	1.2097 $\pm 0.0383$	0.7048 $\pm 0.1833$	92.3	1300	(1): 90 $\pm$ 9	20	0.88	3.73	0.72	142
	dentine	28.19 $\pm 1.64$	1.2468 $\pm 0.0070$	0.8435 $\pm 0.0155$	116.8	$\pm 130$	(2): 120 $\pm$ 12	$\pm 3$	$\pm 0.02$	$\pm 0.02$	$\pm 0.02$	$\pm 4$
T4	enamel	0.41 $\pm 0.14$	1.2398 $\pm 0.0471$	1.3390 $\pm 0.1092$	656.2	900	(1): 110 $\pm$ 11	21	1.47	3.52	0.67	165
	dentine	24.10 $\pm 1.97$	1.3209 $\pm 0.0102$	1.0818 $\pm 0.0175$	165.5	$\pm 90$	(2): 90 $\pm$ 9	$\pm 3$	$\pm 0.02$	$\pm 0.02$	$\pm 0.02$	$\pm 2$
T5	enamel	0.71 $\pm 0.27$	1.3082 $\pm 0.0475$	1.2751 $\pm 0.0742$	265.7	970	(1): 50 $\pm$ 5	21	1.47	3.52	0.67	155
	dentine	23.04 $\pm 0.93$	1.3608 $\pm 0.0084$	1.2050 $\pm 0.0585$	196.1	$\pm 97$	(2): 80 $\pm$ 8	$\pm 3$	$\pm 0.02$	$\pm 0.02$	$\pm 0.02$	$\pm 4$
T6	enamel	0.41 $\pm 0.12$	1.1931 $\pm 0.0360$	0.8108 $\pm 0.0746$	118.8		(1): 30 $\pm$ 3					
	dentine	27.85 $\pm 2.43$	1.2029 $\pm 0.0069$	0.8059 $\pm 0.0067$	115.7	890 $\pm 89$	(2): 60 $\pm$ 6	21 $\pm 3$	0.88 $\pm 0.02$	3.73 $\pm 0.02$	0.72 $\pm 0.02$	153 $\pm 4$
	cementum	29.98 $\pm 6.69$	1.2836 $\pm 0.0059$	0.8287 $\pm 0.0326$	107.5							
T7	enamel	0.49 $\pm 0.18$	1.2791 $\pm 0.0578$	0.7844 $\pm 0.1109$	99.1		(1): 20 $\pm$ 2					
	dentine	29.90 $\pm 1.15$	1.2096 $\pm 0.0080$	0.7702 $\pm 0.0055$	106.2	1050 $\pm 105$	(2): 60 $\pm$ 6	21 $\pm 3$	0.88 $\pm 0.02$	3.73 $\pm 0.02$	0.72 $\pm 0.02$	164 $\pm 4$
	cementum	37.26 $\pm 1.27$	1.3047 $\pm 0.0105$	0.7773 $\pm 0.0124$	94.5							
T8	enamel	0.82 $\pm 0.37$	1.3203 $\pm 0.0437$	1.1941 $\pm 0.1182$	209.8	840	(1): 40 $\pm$ 4	20	0.87	3.77	0.72	254
	dentine	17.76 $\pm 0.46$	1.3777 $\pm 0.0089$	1.3479 $\pm 0.0132$	259.6	$\pm 84$	(2): 60 $\pm$ 6	$\pm 3$	$\pm 0.02$	$\pm 0.02$	$\pm 0.02$	$\pm 4$

Sample	Dental tissue	p U-uptake parameter (a.u.)	$D_{\text{internal}}$ ( $\mu\text{Gy/a}$ )	$D_{\text{dentine}}$ ( $\mu\text{Gy/a}$ )	$D_{\text{sediment}}$ ( $\mu\text{Gy/a}$ )	$D_{(\gamma+\text{cosm})}$ ( $\mu\text{Gy/a}$ )	$D_a$ ( $\mu\text{Gy/a}$ )	ESR-U-series age (ka)	CS-US-ESR age (ka)
T1	enamel	-0.09 $\pm$ 0.27							
	dentine	-0.51 $\pm$ 0.20	56 $\pm$ 16	133 $\pm$ 33	61 $\pm$ 11	405 $\pm$ 55	656 $\pm$ 67	184 + 26 - 19	201 $\pm$ 25
T2	enamel	-0.93 $\pm$ 0.06							
	dentine	-0.93 $\pm$ 0.06	185 $\pm$ 33	344 $\pm$ 63	68 $\pm$ 12	405 $\pm$ 52	1003 $\pm$ 88	174 +17 -14	188 $\pm$ 21
T3	enamel	-0.12 $\pm$ 0.50							
	dentine	-0.49 $\pm$ 0.14	71 $\pm$ 40	173 $\pm$ 36	55 $\pm$ 10	381 $\pm$ 48	680 $\pm$ 72	208 $\pm$ 28 -22	236 $\pm$ 29
<b>Weighted mean</b>								<b>194 + 14 -11</b>	<b>211 <math>\pm</math> 15</b>

Sample	Dental tissue	U (ppm)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{238}\text{U}$	Apparent U-series age (ka)	$^{222}\text{Rn}/^{230}\text{Th}$	Initial enamel thickness ( $\mu\text{m}$ )	Removed thickness ( $\mu\text{m}$ )	Mean depth (m) *	$D_e$ (Gy)																																																																																																																																																																																																																																																											
TVL 157	enamel	$0.594 \pm 0.024$	$1.441 \pm 0.069$	$1.222 \pm 0.101$	174	0.334		(1) $21 \pm 3$	$14 \pm 3$	$220.08 \pm 2.33$																																																																																																																																																																																																																																																											
	dentine	$25.342 \pm 0.580$	$1.306 \pm 0.026$	$1.028 \pm 0.052$	153	0.366	$959 \pm 17$	(2) $74 \pm 9$			TVL 160	enamel	$0.402 \pm 0.016$	$1.313 \pm 0.060$	$1.155 \pm 0.102$	195	1.000	$1050 \pm 131$	(1) $28 \pm 3$	$14 \pm 3$	$207.72 \pm 2.72$	dentine	$22.504 \pm 0.486$	$1.333 \pm 0.026$	$1.152 \pm 0.049$	186	0.340	(2) $160 \pm 20$	TVL 219	enamel	$0.671 \pm 0.022$	$1.259 \pm 0.043$	$0.993 \pm 0.081$	155	0.405	$1027 \pm 128$	(1) $14 \pm 2$	$14 \pm 3$	$204.54 \pm 2.49$	dentine	$31.541 \pm 0.636$	$1.274 \pm 0.022$	$0.956 \pm 0.048$	140	0.378	(2) $167 \pm 21$	TRV 923	enamel	$0.490 \pm 0.018$	$1.301 \pm 0.054$	$1.106 \pm 0.094$	181	0.259	$958 \pm 120$	(1) $68 \pm 9$	$14 \pm 3$	$204.56 \pm 1.09$	dentine	$29.026 \pm 0.741$	$1.261 \pm 0.028$	$1.005 \pm 0.058$	159	0.293	(2) $76 \pm 9$	TRV 928	enamel	$0.296 \pm 0.014$	$1.409 \pm 0.076$	$1.305 \pm 0.116$	217	0.258	$1268 \pm 159$	(1) $200 \pm 25$	$14 \pm 3$	$191.33 \pm 5.82$	dentine	$19.976 \pm 0.348$	$1.311 \pm 0.021$	$1.053 \pm 0.083$	159	0.523	(2) $148 \pm 18$	TVL 929(a)	enamel	$0.374 \pm 0.013$	$1.236 \pm 0.047$	$0.973 \pm 0.086$	155	0.247	$1200 \pm 150$	(1) $112 \pm 14$	$14 \pm 3$	$191.95 \pm 2.73$	dentine	$3.046 \pm 0.067$	$1.263 \pm 0.025$	$0.988 \pm 0.054$	153	1.000	(2) $60 \pm 8$	Sample	Sediment radioelement contents			Dental tissue	p U-uptake parameter (a.u.)	$D_\alpha$ ( $\mu\text{Gy/a}$ )	$D_\beta$ ( $\mu\text{Gy/a}$ )	$D_{(\gamma+\text{cosm})}$ ( $\mu\text{Gy/a}$ )	$D_a$ ( $\mu\text{Gy/a}$ )	US-ESR age (ka)	CSUS-ESR age (ka)	U (ppm)	Th (ppm)	K (%)	TVL 157	1.072	4.005	0.894	enamel	$-0.83 \pm 0.04$	139	305	517	961	229	252	$\pm 0.086$	$\pm 0.114$	$\pm 0.014$	dentine	$-0.72 \pm 0.05$	$\pm 27$	$\pm 42$	$\pm 29$	$\pm 58$	$\pm 13$	$\pm 16$	TVL 160	1.252	4.341	0.902	enamel	$-0.91 \pm 0.03$	100	294	517	911	228	239	$\pm 0.074$	$\pm 0.099$	$\pm 0.011$	dentine	$-0.88 \pm 0.03$	$\pm 19$	$\pm 44$	$\pm 29$	$\pm 56$	$\pm 13$	$\pm 12$	TVL 219	1.293	3.807	0.853	enamel	$-0.82 \pm 0.05$	142	349	517	1008	203	223	$\pm 0.076$	$\pm 0.102$	$\pm 0.012$	dentine	$-0.73 \pm 0.05$	$\pm 28$	$\pm 55$	$\pm 29$	$\pm 61$	$\pm 13$	$\pm 14$	TRV 923	1.065	3.716	0.837	enamel	$-0.88 \pm 0.04$	103	314	517	934	219	232	$\pm 0.063$	$\pm 0.084$	$\pm 0.010$	dentine	$-0.78 \pm 0.04$	$\pm 21$	$\pm 47$	$\pm 29$	$\pm 59$	$\pm 13$	$\pm 14$	TRV 928	1.120	3.735	0.799	enamel	$-0.93 \pm 0.03$	75	176	517	768	249	268	$\pm 0.078$	$\pm 0.103$	$\pm 0.012$	dentine	$-0.69 \pm 0.05$	$\pm 26$	$\pm 39$	$\pm 29$	$\pm 55$	$\pm 15$	$\pm 15$	TVL 929(a)	1.151	3.678	0.807	enamel	$-0.74 \pm 0.04$	65	271	517	853	225	240	$\pm 0.086$	$\pm 0.114$	$\pm 0.014$	dentine	$-0.73 \pm 0.05$	$\pm 14$	$\pm 43$	$\pm 29$	$\pm 54$	$\pm 13$	$\pm 13$	<b>Weighted mean</b>							
TVL 160	enamel	$0.402 \pm 0.016$	$1.313 \pm 0.060$	$1.155 \pm 0.102$	195	1.000	$1050 \pm 131$	(1) $28 \pm 3$	$14 \pm 3$	$207.72 \pm 2.72$																																																																																																																																																																																																																																																											
	dentine	$22.504 \pm 0.486$	$1.333 \pm 0.026$	$1.152 \pm 0.049$	186	0.340		(2) $160 \pm 20$			TVL 219	enamel	$0.671 \pm 0.022$	$1.259 \pm 0.043$	$0.993 \pm 0.081$	155	0.405	$1027 \pm 128$	(1) $14 \pm 2$	$14 \pm 3$	$204.54 \pm 2.49$	dentine	$31.541 \pm 0.636$	$1.274 \pm 0.022$	$0.956 \pm 0.048$	140	0.378	(2) $167 \pm 21$	TRV 923	enamel	$0.490 \pm 0.018$	$1.301 \pm 0.054$	$1.106 \pm 0.094$	181	0.259	$958 \pm 120$	(1) $68 \pm 9$	$14 \pm 3$	$204.56 \pm 1.09$	dentine	$29.026 \pm 0.741$	$1.261 \pm 0.028$	$1.005 \pm 0.058$	159	0.293	(2) $76 \pm 9$	TRV 928	enamel	$0.296 \pm 0.014$	$1.409 \pm 0.076$	$1.305 \pm 0.116$	217	0.258	$1268 \pm 159$	(1) $200 \pm 25$	$14 \pm 3$	$191.33 \pm 5.82$	dentine	$19.976 \pm 0.348$	$1.311 \pm 0.021$	$1.053 \pm 0.083$	159	0.523	(2) $148 \pm 18$	TVL 929(a)	enamel	$0.374 \pm 0.013$	$1.236 \pm 0.047$	$0.973 \pm 0.086$	155	0.247	$1200 \pm 150$	(1) $112 \pm 14$	$14 \pm 3$	$191.95 \pm 2.73$	dentine	$3.046 \pm 0.067$	$1.263 \pm 0.025$	$0.988 \pm 0.054$	153	1.000	(2) $60 \pm 8$	Sample	Sediment radioelement contents			Dental tissue	p U-uptake parameter (a.u.)	$D_\alpha$ ( $\mu\text{Gy/a}$ )	$D_\beta$ ( $\mu\text{Gy/a}$ )	$D_{(\gamma+\text{cosm})}$ ( $\mu\text{Gy/a}$ )	$D_a$ ( $\mu\text{Gy/a}$ )	US-ESR age (ka)	CSUS-ESR age (ka)	U (ppm)	Th (ppm)	K (%)	TVL 157	1.072	4.005	0.894	enamel	$-0.83 \pm 0.04$	139	305	517	961	229	252	$\pm 0.086$	$\pm 0.114$	$\pm 0.014$	dentine	$-0.72 \pm 0.05$	$\pm 27$	$\pm 42$	$\pm 29$	$\pm 58$	$\pm 13$	$\pm 16$	TVL 160	1.252	4.341	0.902	enamel	$-0.91 \pm 0.03$	100	294	517	911	228	239	$\pm 0.074$	$\pm 0.099$	$\pm 0.011$	dentine	$-0.88 \pm 0.03$	$\pm 19$	$\pm 44$	$\pm 29$	$\pm 56$	$\pm 13$	$\pm 12$	TVL 219	1.293	3.807	0.853	enamel	$-0.82 \pm 0.05$	142	349	517	1008	203	223	$\pm 0.076$	$\pm 0.102$	$\pm 0.012$	dentine	$-0.73 \pm 0.05$	$\pm 28$	$\pm 55$	$\pm 29$	$\pm 61$	$\pm 13$	$\pm 14$	TRV 923	1.065	3.716	0.837	enamel	$-0.88 \pm 0.04$	103	314	517	934	219	232	$\pm 0.063$	$\pm 0.084$	$\pm 0.010$	dentine	$-0.78 \pm 0.04$	$\pm 21$	$\pm 47$	$\pm 29$	$\pm 59$	$\pm 13$	$\pm 14$	TRV 928	1.120	3.735	0.799	enamel	$-0.93 \pm 0.03$	75	176	517	768	249	268	$\pm 0.078$	$\pm 0.103$	$\pm 0.012$	dentine	$-0.69 \pm 0.05$	$\pm 26$	$\pm 39$	$\pm 29$	$\pm 55$	$\pm 15$	$\pm 15$	TVL 929(a)	1.151	3.678	0.807	enamel	$-0.74 \pm 0.04$	65	271	517	853	225	240	$\pm 0.086$	$\pm 0.114$	$\pm 0.014$	dentine	$-0.73 \pm 0.05$	$\pm 14$	$\pm 43$	$\pm 29$	$\pm 54$	$\pm 13$	$\pm 13$	<b>Weighted mean</b>									<b><math>224 \pm 11</math></b>	<b><math>241 \pm 11</math></b>															
TVL 219	enamel	$0.671 \pm 0.022$	$1.259 \pm 0.043$	$0.993 \pm 0.081$	155	0.405	$1027 \pm 128$	(1) $14 \pm 2$	$14 \pm 3$	$204.54 \pm 2.49$																																																																																																																																																																																																																																																											
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Sample	Level	U (ppm)	Th (ppm)	K (%)	AI Bleaching coefficient (%)	D <sub>e</sub> (Gy)	D <sub>α</sub> (μGy/a)	D <sub>β</sub> (μGy/a)	in situ D <sub>γ</sub> (μGy/a)	D <sub>cosmic</sub> (μGy/a)	D <sub>a</sub> (μGy/a)	Age (ka)
Tourville 1	D2	1.014 ±	3.270 ±	0.748 ±	44	409	26	622	393	102	1144	358
		0.074	0.103	0.012		± 56	± 1	± 17	± 20	± 5	± 22	± 50
Tourville 2	D2	0.895 ±	3.133 ±	0.728 ±	42	398	24	595	418	102	1139	349
		0.083	0.114	0.014		± 30	± 1	± 19	± 20	± 5	± 50	± 30
Tourville 3	D2	0.993 ±	3.460 ±	0.756 ±	49	708	27	629	412	102	1170	605
		0.086	0.118	0.014		± 87	± 1	± 20	± 20	± 5	± 26	± 80
Tourville 4	D2	0.990 ±	3.567 ±	0.741 ±	51	1085	27	621	447	102	1198	906
		0.072	0.099	0.012		± 76	± 1	± 17	± 20	± 5	± 21	± 70
Tourville 5	D1	0.767 ±	1.677 ±	0.426 ±	46	246	16	370	260	89	736	334
		0.046	0.057	0.006		± 32	± 1	± 10	± 13	± 4	± 13	± 90
Tourville 6	D1	0.711 ±	1.978 ±	0.447 ±	46	295	18	389	260	89	756	390
		0.067	0.080	0.010		± 40	± 1	± 15	± 13	± 4	± 19	± 60



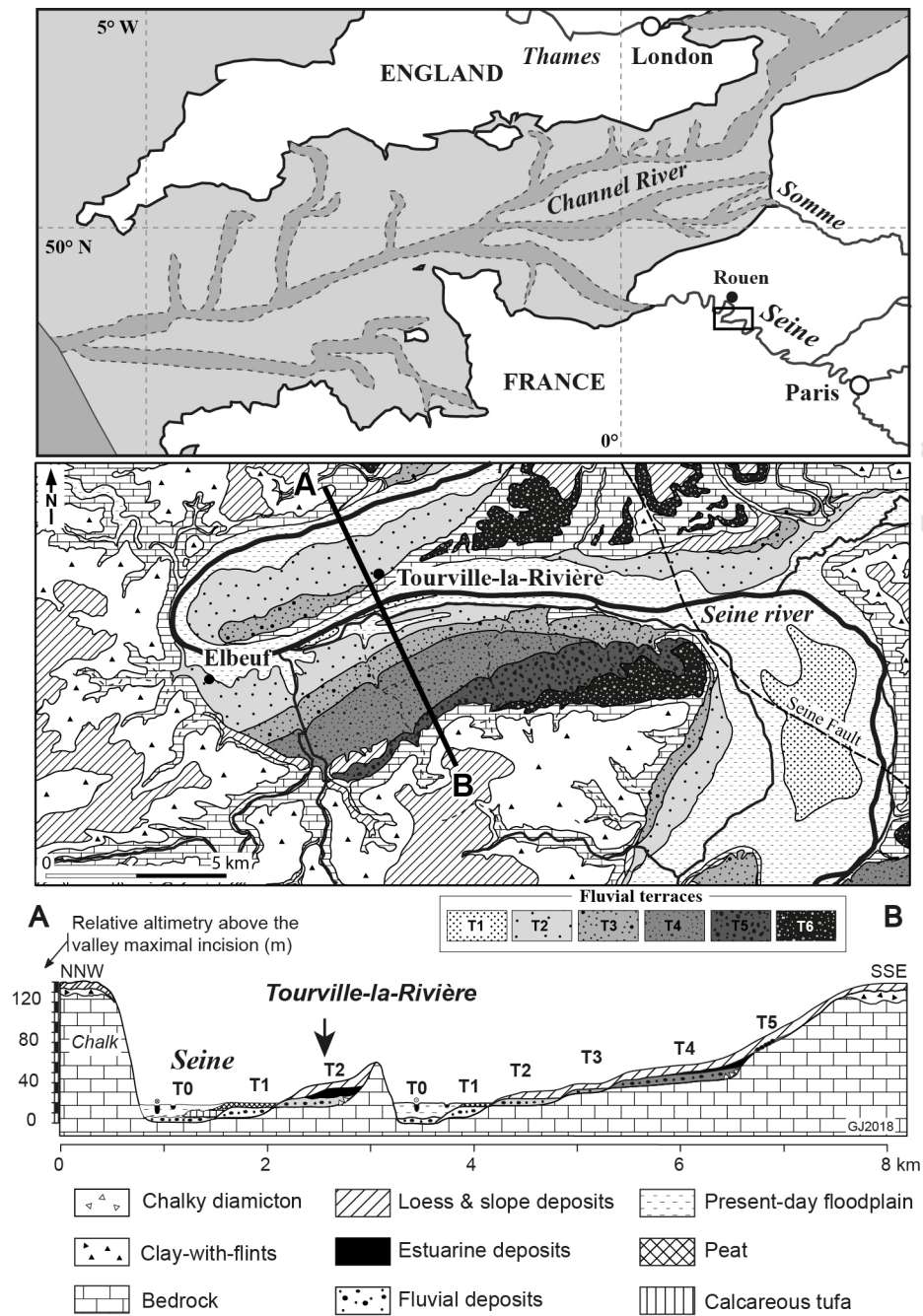
Sample	CENIEH-RSES (Favre et al., 2014)			This study			Ratio
	D <sub>e-1</sub> (Gy)	D <sub>max</sub> (Gy)	D <sub>max</sub> /D <sub>e-1</sub>	D <sub>e-2</sub> (Gy)	D <sub>max</sub> (Gy)	D <sub>max</sub> /D <sub>e-2</sub>	
T1	121 ± 2	5,000	41	121 ± 3	1,000	8	1.00
T2	175 ± 2	5,000	29	178 ± 4	1,000	6	1.02
T3	142 ± 4	5,000	35	134 ± 4	1,000	7	0.94
T4	165 ± 2	5,000	30	160 ± 2	1,000	6	0.97
T5	155 ± 4	5,000	32	150 ± 7	1,000	7	0.97
T6	153 ± 4	5,000	33	149 ± 7	1,000	7	0.97
T7	164 ± 4	5,000	30	151 ± 5	1,000	7	0.92
T8	254 ± 4	5,000	20	251 ± 8	1,800	7	0.99
<b>Mean ± s.d.</b>	<b>166 ± 28 (17%)</b>			<b>153 ± 22 (14%)</b>			<b>0.97</b>

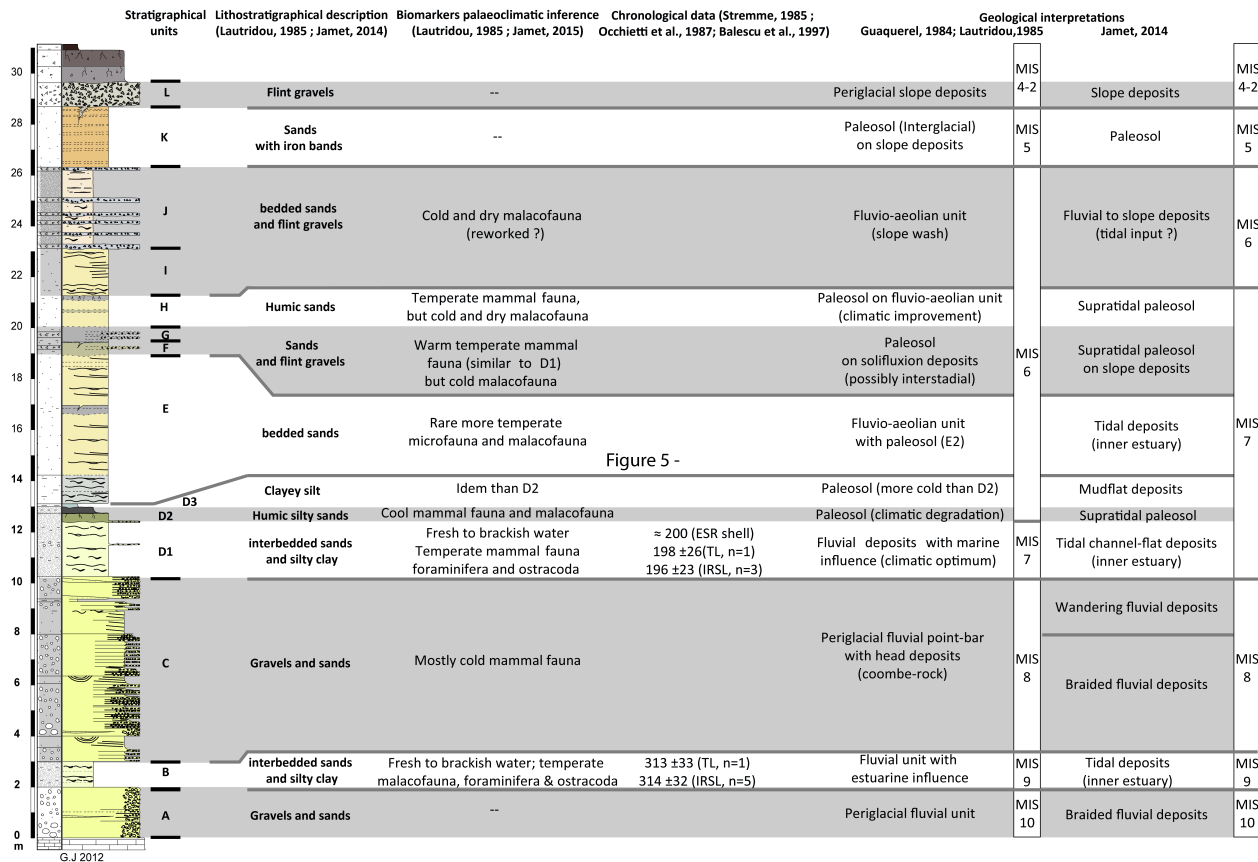
  

Sample	MNHN (Bahain et al., 2015)			This study			Ratio
	D <sub>e-1</sub> (Gy)	D <sub>max</sub> (Gy)	D <sub>max</sub> /D <sub>e-1</sub>	D <sub>e-2</sub> (Gy)	D <sub>max</sub> (Gy)	D <sub>max</sub> /D <sub>e-2</sub>	
TVL157	221 ± 3	5,000	23	217 ± 7	1,249	6	0.98
TVL160	208 ± 3	5,000	24	206 ± 6	1,249	6	0.99
TVL219c	205 ± 2	5,000	24	193 ± 5	1,249	6	0.94
TVL923	205 ± 1	5,000	24	201 ± 3	1,249	6	0.98
TVL928	191 ± 6	5,000	23	169 ± 6	1,249	7	0.88
TVL929	191 ± 6	5,000	26	183 ± 4	1,249	7	0.96
<b>Mean ± s.d.</b>	<b>207 ± 6 (3%)</b>			<b>195 ± 14 (7%)</b>			<b>0.96</b>

Analytical steps	CENIEH-RSES	MNHN
<i>Preparation</i>		Mechanic with dentist drill
<i>Selected grain size</i>		100-200 $\mu\text{m}$
<i>Impact of preparation on alpha and beta dose rate</i>	Data from Marsh (1999)	Data from Brennan et al. (1997)
<i>Number of dose irradiation steps</i>		10
<i>Maximum irradiation dose (<math>D_{max}</math>)</i>		5,000 Gy
<i>Measurement of the ESR intensity</i>		Peak-to-peak amplitude (T1B2; Grun, 2000b)
<i>Fitting function - data weighting</i>	Single Saturating Exponential (SSE) – Inverse of the squared ESR intensities ( $1/I^2$ )	
<i>Fitting program</i>		Origin
<i>U-series analyses of dental tissues</i>	High resolution Laser Ablation ICP-MS analyses (as in Grün et al., 2014) The U-series data from all the laser ablation spots of a given tissue were combined to provide the data input for the ESR age calculations	Solution alpha spectrometry bulk analyses
<i>Alpha efficiency</i>		0.13 $\pm$ 0.02 (Grün and Katzenberger-Apel, 1994)
<i>Rn loss in dental tissues</i>	Equilibrium was assumed	Determined by cross-checking data from High resolution gamma spectrometry (HRGS) and alpha spectrometry analyses
<i>Water content of dental tissues</i>	Enamel = 0 % wgt Dentine = 5 $\pm$ 3 % wgt	Enamel = 0 % wgt Dentine = 7 $\pm$ 5 % wgt
<i>Radioelement contents in sediment</i>	Determined by ICP-MS/OES The values were used to derive the beta and gamma dose rates	Determined by HRGS The values were used to derive the beta dose rates
<i>Water content of sediment</i>	20 $\pm$ 10 % wgt	15 $\pm$ 5 % wgt
<i>Dose rate conversion factors</i>	Guérin et al. (2011)	Adamiec and Aitken (1998)
<i>In situ gamma measurements</i>	No (gamma dose rate calculated from radioelement contents)	Yes (NaI probe connected to a Inspector1000 Canberra multichannel analyzer) on a section close to the excavation area. Gamma dose rates were obtained with the Threshold method (Mercier and Falguères, 2007). A mean gamma dose rate was derived from the 4 in situ measurements performed within layer D2.
<i>Cosmic dose rate</i>	Calculated from present-day depth (according with the tables of Prescott and Hutton, 1988, 1994)	Calculated using a three stage model evolution based on Jamet's geological interpretation (according with the tables of Prescott and Hutton, 1988, 1994)
<i>Age calculation program</i>	DATA program (US-ESR and CS-USESR ages) (Grün, 2009)	USESR (US, Shao et al., 2014) and DATA (CS-US, Grün, 2009) programs

Analytical protocol	MNHN	BRGM
<i>Preparation</i>	Quartz extraction and purification procedure following Voinchet et al. (2004)	
<i>Selected grain size</i>	100-200 $\mu\text{m}$	
<i>Number of irradiation steps</i>	10	
<i>D<sub>max</sub></i>	9,870 Gy	11,700 Gy
<i>ESR signal</i>	Al (Toyoda and Falguères, 2003)	Al (Toyoda and Falguères, 2003), Ti-Li and Ti-H (Toyoda et al., 2000 ; Tissoux et al., 2008)
<i>ESR intensity</i>	Al -From the top of the peak at $g = 2.018$ and the bottom of the 16th peak at $g = 2.002$	Ti-Li - from the bottom of the peak at $g = 1.913$ to the baseline Ti-H - from the bottom of the doublet at $g = 1.915$ to the baseline
<i>Fitting function (data weighting)</i>	E+L (1/12)	
<i>Fitting program</i>	Origin	
<i>Alpha efficiency</i>	0.15 $\pm$ 0.10 (Laurent et al., 1998)	
<i>Sediment radioelement contents</i>	Determined by HRGS	
<i>Post Rn disequilibrium in the U-238 series</i>	No disequilibrium observed	
<i>Water content of sediment</i>	Measured values (5-8 % wgt)	15 $\pm$ 5 % wgt (measured values :10-12% wgt)
<i>In situ gamma measurements</i>	Yes (NaI probe, Inspector 1000, Canberra), directly at the sampling spot	Yes (NaI probe, Digidart LF gamma, Ortec), directly at the sampling spot
<i>Cosmic dose rate</i>	Calculated from present-day depth (according to the tables of Prescott and Hutton, 1988, 1994)	
<i>Grain size attenuation for alpha and beta dose rate</i>	Brennan (2003) and Brennan et al. (1991)	
<i>Dose rate factor conversions</i>	Adamiec and Aitken (1998)	
<i>Age calculation program</i>	ESR MNHN program	





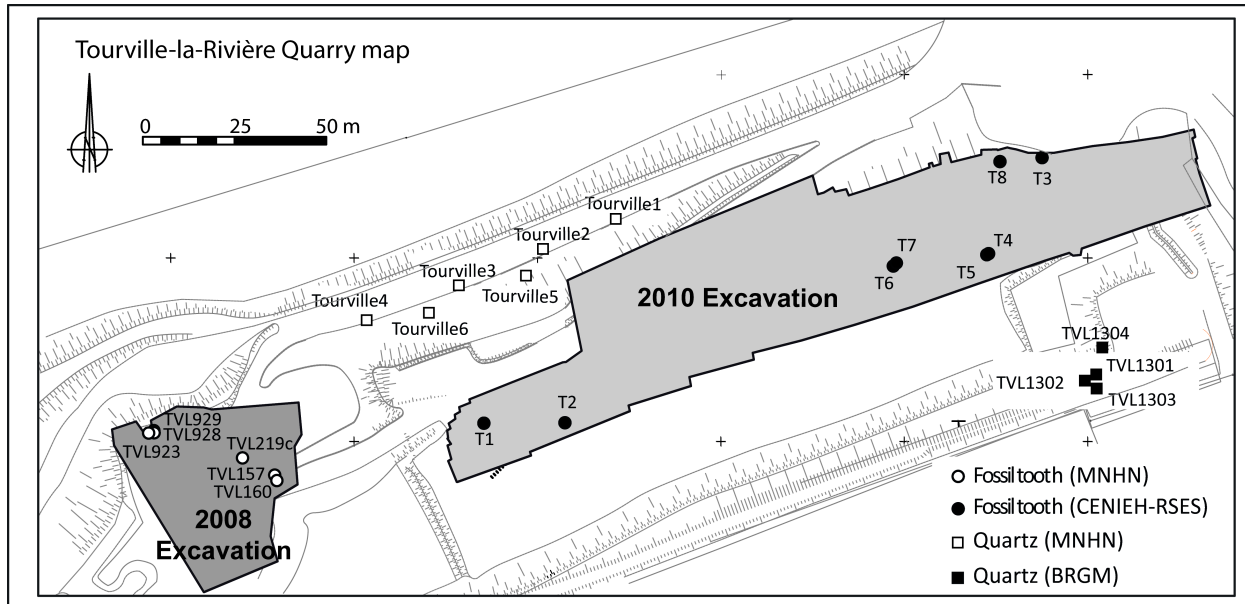


Figure 3 - Tourville



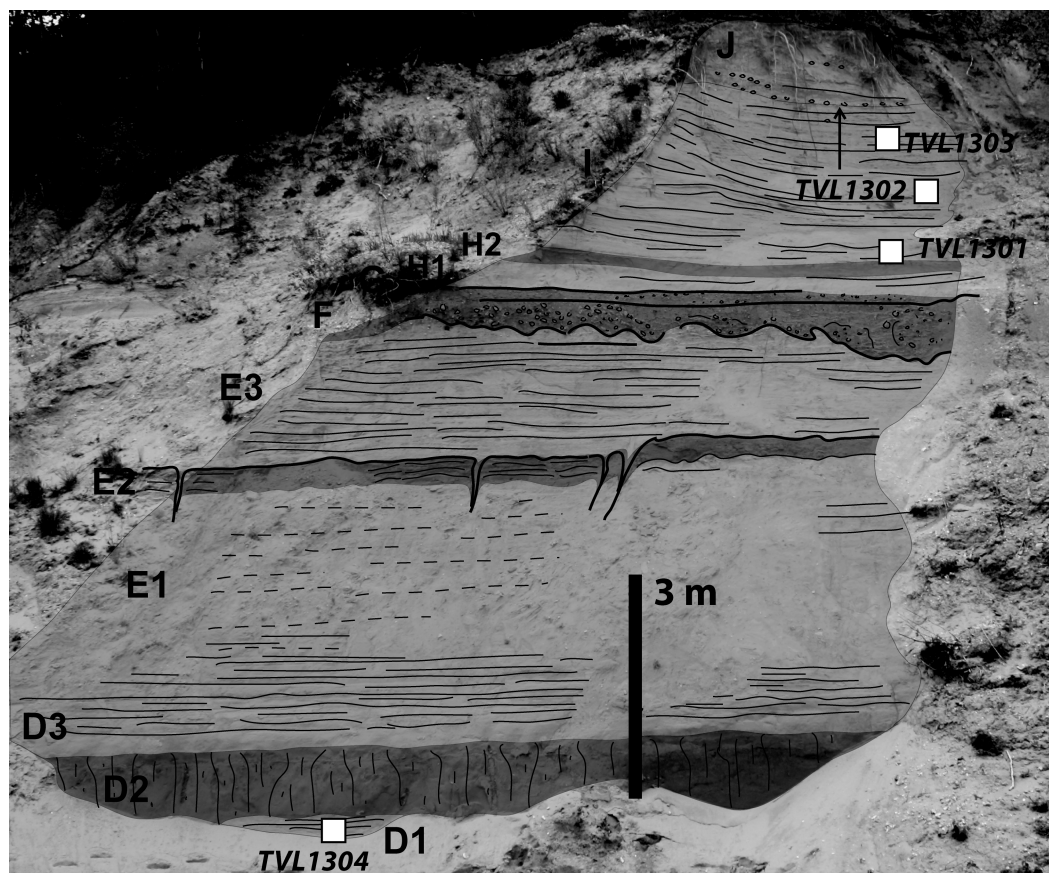
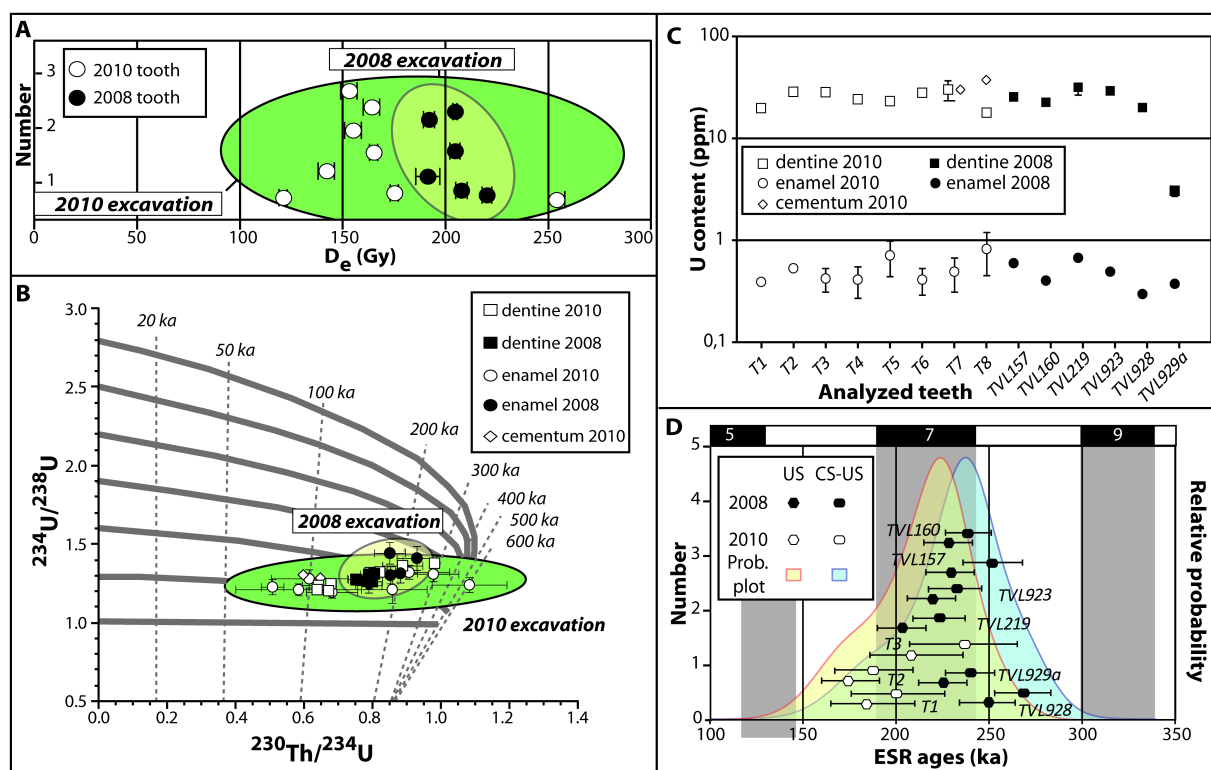


Figure 4 - Tourville

Figure 5 - Tourville



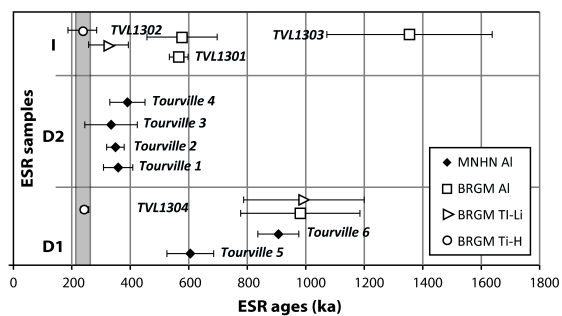


Figure 6 - Tourville