



HAL
open science

Chronology of the Upper Pleistocene loess sequence of Havrincourt (France) and associated Palaeolithic occupations: a Bayesian approach from pedostratigraphy, OSL, radiocarbon, TL and ESR/U-series data

Gilles Guérin, Pierre Antoine, Esther Schmidt, Emilie Goval, David Hérison, Guillaume Jamet, Jean-Louis Reyss, Qingfeng Shao, Anne Philippe, Marie-Anne Vibet, et al.

► To cite this version:

Gilles Guérin, Pierre Antoine, Esther Schmidt, Emilie Goval, David Hérison, et al.. Chronology of the Upper Pleistocene loess sequence of Havrincourt (France) and associated Palaeolithic occupations: a Bayesian approach from pedostratigraphy, OSL, radiocarbon, TL and ESR/U-series data. *Quaternary Geochronology*, 2017, 42, pp.15-30. 10.1016/j.quageo.2017.07.001 . hal-01584140

HAL Id: hal-01584140

<https://hal.science/hal-01584140v1>

Submitted on 22 Sep 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Chronology of the Upper Pleistocene loess sequence of Havrincourt**
2 **(France) and associated Palaeolithic occupations: a Bayesian approach**
3 **from pedostratigraphy, OSL, radiocarbon, TL and ESR/U-series data**

4

5 *Gilles Guérin (1), Pierre Antoine (2), Esther Schmidt (1), Emilie Goval (3), David Hérisson*
6 *(4), Guillaume Jamet (5), Jean-Louis Reyss (1), Qingfeng Shao (6), Anne Philippe (7), Marie-*
7 *Anne Vibet (7), Jean-Jacques Bahain (8)*

8

9 1) Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-
10 UVSQ, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France;

11 G. Guérin (gilles.guerin@lsce.ipsl.fr),

12 E. Schmidt (estherdorothe.car@gmail.com),

13 J.-L. Reyss (Jean-Louis.Reyss@lsce.ipsl.fr),

14 2) Laboratoire de Géographie Physique Environnements quaternaires et actuels (UMR 8591,
15 CNRS-Universités Paris I & Paris XII), 1 place Aristide Briand, F-92195 Meudon cedex
16 (pierre.antoine@cnrs-bellevue.fr)

17 3) Service Régional de l'Archéologie / DRAC Nord-pas-de-Calais-Picardie, 1 rue Henri
18 Daussy, F-80000 Amiens, France (emilie.goval@culture.gouv.fr)

19 4) INRAP Canal Seine-Nord Europe, 16 rue du Général Leclerc, F-80400, Croix-Moligneaux
20 and UMR 7194 CNRS, Institut de Paléontologie Humaine, 1 rue René Panhard, F-75013,
21 Paris, France (david.herisson@inrap.fr)

22 5) GéoArchÉon SARL, 30, rue de la Victoire, F-55210 Viéville-sous-les-Côtes, France
23 (guillaume.jamet@geoarcheon.fr)

24 6) College of Geography Science, Nanjing Normal University, Nanjing 210023, China; Q.
25 Shao (qingfengshao@nynu.edu.cn)

26 7) Laboratoire de Mathématiques Jean Leray Université de Nantes. 2, rue de la Houssinière
27 Po Box 92208, F-44322 Nantes, France (Anne.Philippe@univ-nantes.fr, [marie-](mailto:marie-anne.vibet@univ-nantes.fr)
28 anne.vibet@univ-nantes.fr)

29 8) Département de Préhistoire du Muséum national d'Histoire naturelle, UMR 7194 CNRS,
30 Institut de Paléontologie Humaine, 1 rue René Panhard, F-75013 Paris, France.
31 (bahain@mnhn.fr),

32 **Abstract**

33 In connection with the future Seine-North Europe Canal (Seine-Scheldt), a large-scale rescue
34 archaeological survey was conducted at Havrincourt (northern France) between 2008 and
35 2011. The discovery of several levels of Palaeolithic flint artefacts embedded in a relatively
36 thick loess sequence (ca 6 to 7 m) preserved on a gentle slope facing North-East, resulted in a
37 6000 m² excavation. This opened the opportunity for a detailed pedosedimentary and
38 interdisciplinary geochronological survey (¹⁴C, optically stimulated luminescence,
39 thermoluminescence, ESR/U-series) that has allowed us date the sequence reliably. On the
40 basis of these results we propose this sequence as a new pedostratigraphic and archaeological
41 reference sequence for northern France. We present here the optical dating of the sequence
42 performed on fine (4-11 µm) quartz grains extracted from 17 samples. The luminescence
43 characteristics of these extracts indicate that the single-aliquot regenerative dose optically
44 stimulated luminescence (SAR-OSL) procedure that was applied is well suited. A consistent
45 set of optical ages was obtained for the loess deposited up to around 70 ka ago. Independent
46 age control (pedostratigraphy, ¹⁴C, ESR/U-series dates) allowed us to apply a Bayesian
47 approach to build a chronometric model. This in turn enabled a regional chronostratigraphic
48 framework to be built, to constrain the correlations with neighboring regions (northern France
49 and Belgium) and to calculate a precise age for the four Palaeolithic levels discovered,
50 including a unique occupation related to the early Upper Palaeolithic which was previously
51 unknown in the area.

52 **Keywords:** Loess; Palaeosols; Northern France; Optical dating; SAR; Quartz; ESR/U-series
53 dating; Periglacial processes; Middle and Upper Palaeolithic; Weichselian

54

55 **1) Introduction**

56 Western European loess-palaeosol sequences preserve a significant terrestrial record of
57 Quaternary history providing a window into the response of terrestrial environments to large
58 scale Interglacial-Glacial cycles (Lautridou et al., 1985; Antoine 1994; Antoine et al., 1998,
59 Meijs 2002, Meijs et al., 2011, Hérissou et al., 2016) and rapid climatic events during the Last
60 Glacial (Rousseau et al., 2002, 2007; Antoine et al., 2009, 2016, Haesaerts et al., 2003, 2010;
61 Moine et al., 2008). In northern France, these deposits have been extensively studied over the
62 last 20 years, in parallel with numerous archaeological investigations on Palaeolithic sites
63 (Antoine 1991; Antoine, 1994; Deschodt et al., 1998; Antoine et al., 1998, 2003a, 2003b,
64 2014, 2016; Locht et al., 2002, 2003; Vallin and Masson 2003; Sellier, 2005;).

65 The site of Havrincourt is located at the western edge of the European loess belt near the town
66 of Cambrai (Pas-de-Calais, France) (Fig. 1). A large-scale study of this pedosedimentary
67 sequence was undertaken alongside rescue archaeology work within the Seine-North-Europe
68 canal project. Between 2008 and 2010, large archaeological surveys (test-pits) were excavated
69 down to 5 to 7 m minimal depth, locally reaching until 12 m, to detect remains of Palaeolithic
70 occupations. This gave us the opportunity to characterize soil horizons (palaeosols)
71 alternating with aeolian and hillwashed sedimentary deposits and periglacial phenomena
72 (tundra gleysols and former large ice-wedge networks). The geological context and the
73 knowledge of the regional records indicate that this sequence belongs to the last climatic cycle
74 of the Eemian-Weichselian (Antoine et al., 1999, 2016). The sequences that were identified
75 represent a reference for Last Glacial soil and sediment records in the north of France
76 (Antoine et al., 2014a, 2016). In this paper we report geochronological results, including 17
77 optical dates obtained on fine grain quartz from the loess, along with ^{14}C and ESR/U-series
78 dates measured on palaeontological remains. These new data are discussed in relation to other
79 dating results (TL dates on heated flints and climato-stratigraphy) using a Bayesian approach
80 in the context of the latest northern France loess-palaeosol chronostratigraphy. The
81 chronological study of this site had the larger aim of providing clues to establish precise and
82 detailed correlations with regional records in northern France and surrounding areas, and
83 finally, to be able to connect the Havrincourt continental sequence with global palaeoclimatic
84 records (Greenland ice and North Atlantic oceanic records).

85

86 **2) Site location and stratigraphy**

87 The Havrincourt site, located on a gentle slope exposed to the north-northeast between 80 and
88 110 m a.s.l., is close to an east-west dry valley belonging to the Schelde River basin. In this
89 sector, well-developed loess-palaeosol sequences are found on white Senonian chalk and can
90 locally reach more than 6 m thickness (exceptionally more than 10 m). Several Palaeolithic
91 sites have also been identified (Vallin and Masson, 2003, Marcy et al., 2009).

92 Archaeological surveys have been carried in two different sectors, separated by about 500 m
93 (Fig. 2) (Havrincourt 1, Hav1, in 2010 and Havrincourt 2, Hav2, in 2011), representing a total
94 of 9 months of study and sampling over a surface of around 6000 m² to an minimal depth of 6
95 m (Hérisson and Goval 2013).

96 The occurrence of a well-preserved complex of soil and loess deposits belonging to the
97 Weichselian Middle and Upper Pleniglacial chronoclimatic phases has produced a very

98 detailed record of environmental changes during this part of the Last Glacial. In addition, the
99 topographic position of the site, coinciding with a gently sloping northeast face, favoured the
100 trapping of loess on the leeward slope, allowing for rapid burial of artifacts and evidence for
101 human presence. The setting up of a morphostratigraphic survey, linked to the Palaeolithic
102 remains, was thus a central part of field investigations.

103 The stratigraphic survey was made both on long profiles exposed along the archaeological
104 excavations (200-300 m long) and on some specific detailed profiles located at the places
105 where pedostratigraphic information was the best-preserved (Fig. 2).

106 Chronostratigraphic and paleoenvironmental investigations were based on systematic and
107 continuous high-resolution sampling of the main profiles (5 to 2.5 cm resolution on the 5-6 m
108 deposit thickness according with profiles) for sedimentology (grain size, CaCO_3),
109 micromorphology, malacology, magnetic susceptibility and soil geochemistry.

110 These observations and analyses allowed us to map a succession of several litho- and pedo-
111 stratigraphic units represented by the following chrono-climatic succession on a synthetic
112 stratigraphic log, from top to bottom (Fig. 3) (Antoine et al., 2014a):

113 Units 0 and 1 - Late Glacial and Holocene: ploughing horizon and Bt horizon of brown
114 leached soil (top soil).

115 Units 2 to 5 - Upper Pleniglacial: calcareous loess and tundra gley horizons.

116 Units 6 and 7 - Middle Pleniglacial: boreal and arctic brown soil horizons.

117 Units 8 to 13 - Lower Pleniglacial: calcareous loess, tundra gley, brownish horizon and
118 laminated colluvial deposits.

119 Unit 14 - Early-Glacial (EGL): grey forest soil and isohumic steppe soil horizons.

120 Unit 15 - Eemian: truncated Bt horizon of brown leached soil.

121 Unit 16 - Saalian: calcareous loess.

122 In addition, several horizons of permafrost features were also identified through the presence
123 of well-developed ice wedge casts indexed from F1 to F5 (Fig. 3). Several archaeological
124 levels including lithic artifacts in association with faunal remains have been discovered in
125 different stratigraphic units (Fig. 4). The oldest archaeological level named Hav2- N0
126 (Havrincourt sector 2, level 0) is located in sedimentary unit 16. This human occupation is
127 characterized by few artifacts but clearly shows that humans were present at Havrincourt
128 during the Saalian stage.

129 Two archaeological levels were recognized within stratigraphical unit 12: Hav1-N3
130 (Havrincourt, sector 1, level 3) and Hav2-N1 (Havrincourt, sector 2, level 1). Two burnt flint
131 pieces, one from each of these two levels, were dated in a previous study by

132 thermoluminescence to 118 ± 12 ka and 102 ± 10 ka respectively (N. Debenham, cited in
133 Antoine et al., 2014a). No lithic refitting and no direct stratigraphic connection have been
134 established between these levels. They may therefore potentially be two distinct human
135 occupations. The lithic series from Hav1-N3 is characterized by the exclusive presence of
136 large Levallois flakes, without any other element of the corresponding “chaîne opératoire”.
137 These flakes are associated with faunal remains (n=70), mainly horse (n=13), bison (n=4) and
138 rhinoceros (n=3). The Hav1-N3 occupation can be interpreted as a hunting site where humans
139 used very standardized flakes both in terms of form and size. The lithic series Hav2-N1
140 highlights a spot of debitage in a steppe landscape turned towards the production of
141 centripetal Levallois flakes of smaller dimensions. Horses (n=3) are the dominant faunal
142 species recorded within this level (n=14).

143 Finally, unit 6a includes the Hav2-N2 occupation (Havrincourt, sector 2, level 2). It is
144 correlated to the early Upper Paleolithic, which is rarely recorded in northern France. In this
145 level, the objective of the lithic production is focused upon laminar products. Horse (n=21),
146 reindeer (n=12) and bison (n=7) are the main faunal species associated with this human
147 occupation, which is interpreted as a short-term campsite comprising activity areas dedicated
148 both to blade production and to the exploitation of animal carcasses (n=238).

149

150 **3) Geochronological studies**

151 **3a) Material and methods**

152 *Radiocarbon*

153 Radiocarbon dating was performed on large mammal remains from archaeological layer
154 Hav2-N2 in unit 6a and from rodent bones preserved within the infilling of the large burrows
155 characterizing the unit 7 soil horizon (Antoine et al., 2014a).

156 Eight faunal remains from Havrincourt sector 2 were selected for AMS radiocarbon dating
157 and sent to two different laboratories, the Oxford Radiocarbon Accelerator Unit (ORAU)(3
158 samples) and Beta Analytic (5 samples). Unfortunately, the quantity of collagen of the three
159 samples sent to Oxford was considered to be insufficient to obtain reliable dates according to
160 their protocol. The analyses were therefore conducted exclusively by Beta Analytic using the
161 following procedure, requiring 2 to 10 g of bone. The sample was dissolved in dilute acid to
162 eliminate apatite and carbonate, to determine the quality of the remaining ‘collagen’. If the
163 quality was acceptable, the sample was then washed in NaOH in order to remove exogenous
164 organic contaminants. This step usually destroys part of the ‘collagen’ but enables a clean
165 sample to be obtained for radiocarbon analyses. After a final acid washing, the remaining

166 'collagen' was dried and the $^{13}\text{C}/^{12}\text{C}$ ratio determined. If the result was acceptable, the ^{14}C
167 dating analysis was performed. In the case of the Havrincourt bones, the application of
168 ultrafiltration was not requested.

169

170 *Optically stimulated luminescence (OSL)*

171 A set of 17 samples was extracted from eight pedosedimentary units from the Havrincourt 1
172 (Hav1) and Havrincourt 2 (Hav2) sites. Sampling points were carefully chosen for their
173 stratigraphic positions and restricted to those showing a good visual homogeneity of the
174 surrounding sediment and no evidence for post-depositional disturbances or diagenesis.
175 Sampling was undertaken using copper tubes (35 mm diameter, 140 mm length) introduced
176 horizontally into the sediment. After extraction they were sealed at both ends to prevent
177 exposure to light. The sampling locations are shown in Figure 5. For dosimetry purposes,
178 about 2 kg of the sediment surrounding the OSL tube was removed and averaged to be
179 representative of a 30 cm diameter zone.

180 Luminescence analyses were performed on polymineral fine (4–11 μm) grains extracted from
181 the inner material of the sampling tubes of which both ends have been discarded. Sample
182 preparation techniques have been performed using usual procedures (Lang et al., 1996;
183 Frechen et al., 1996). Organic matter was eliminated using a hydrogen peroxide treatment
184 (40%, 24 h) then quartz grains were isolated by etching for 5 to 12 days in hydrofluorosilicic
185 acid (H_2SiF_6) followed by rinsing in hydrochloric acid (3N, 5 h). Aliquots were prepared by
186 settling of a 1 mg/ml suspension on 10 mm diameter stainless steel discs. Final quartz deposit
187 is about 1 mg/cm². All luminescence measurements were performed using a Risø TL/OSL-
188 DA-15 system equipped with blue (470 nm) light-emitting diodes and an IR (830 nm) laser
189 diode (Bøtter-Jensen et al., 2002). The luminescence signals were detected through a 7.5 mm
190 thick Hoya U-340 filter.

191 Each quartz fraction was checked for purity by an IR-test on three discs (regenerative dose of
192 ca 20 Gy, preheating at 260 °C for 10 s, IR-stimulation at 50 °C for 40 s, blue-light simulation
193 at 125 °C for 40 s). For all samples, the sensitivity to infrared stimulation was close to or less
194 than 1% of the corresponding OSL signal, much lower than the 10% generally accepted
195 (Vandenbergh 2004), and the IR depletion ratio (Duller 2003) deviated less than 1.5% from
196 unity.

197 Irradiations were performed with the $^{90}\text{Sr}/^{90}\text{Y}$ source of the TL-OSL reader. Its dose-rate on
198 01/01/2008 is 0.153Gy/s and has been calibrated using fine grains quartz deposits in the same
199 conditions as OSL measurements. This calibration uses a ^{137}Cs gamma source as reference

200 (Guérin and Valladas, 2014). Alpha efficiency factors were measured using an alpha irradiator
201 equipped with a 3.7 MBq ^{241}Am source with an 8 mm diameter emission surface emitting
202 $7.68 \cdot 10^5$ alpha/cm²/s. Sample irradiations were performed in a vacuum chamber (in order to
203 preserve an incident energy for the alpha beam of about 5.2 MeV) using 6 mm diameter discs
204 with a close to 1 mg/cm² sample deposit.

205 The luminescence determination of the equivalent doses was achieved using a single-aliquot
206 regenerative-dose (SAR) procedure (Murray and Wintle, 2000). All samples have similar OSL
207 behaviour. The OSL signal shows a 90% decrease of the signal in less than 1.1 s (Fig. 6). The
208 signal has been integrated on the first 2 seconds of stimulation minus the background
209 determined on the interval 33-35 s. The total blue stimulation is 36.7 s at 125 °C and 90% of
210 blue LED power (ca 20 mW/cm² based on manufacturer's information). Each measurement
211 was followed by a test dose of 10 Gy and cutheat at 180 °C for 1 s. The OSL measurement
212 (Tx) gives the corrected OSL signal L_x/T_x .

213 Parameters of the SAR protocol were fixed individually for each sample. The preheat
214 temperature is chosen when the following 3 conditions are met. First, satisfaction of the
215 preheat plateau test. This test was performed for all the samples for preheat temperatures
216 ranging from 180 °C to 320 °C with a 20 °C step (Fig. 7). The detailed protocol is
217 summarized in Table 1. The second condition is the value of the recycling ratio that must be
218 close to unity (within a few percent). The last is the fulfilment of the dose recovery test
219 (Murray and Wintle 2003). For 8 samples, the determination of the value for preheat
220 temperature was achieved using an additional "preheat recovery test" where, as for natural
221 signal, the given dose is measured for preheat temperatures ranging from 180 °C to 320 °C
222 with a 20 °C step. We performed the dose recovery test by bleaching our sample with blue
223 LEDs (ca 20 mW/cm²) at 125 °C for 600 s. Since its introduction, it has been noted that the
224 dose recovery test may depend on the way the sample is bleached, or for some other reason,
225 and may not be universal (Wang et al., 2011). We checked this aspect on five samples by
226 bleaching the OSL signal using a solar simulator (3 h exposure at 5 cm with a 250 W Osram-
227 Powerstar HQI-T). They showed no difference in the recovery test. Other tests were done on
228 some samples as follows. Without bleaching of the natural signal, some aliquots were
229 irradiated with a test dose Δ and then measured by SAR. The extrapolated dose of these
230 aliquots D_{add} should be equal to the sum of the test dose Δ and the extrapolated dose
231 D_e of natural sample aliquots. This test can be expressed by the ratio
232 $(D_{\text{add}}-D_e)/\Delta$ that must be close to unity. Doing this prevents some
233 unanticipated influence of bleaching in determining the recovery dose

234 and can be done at the same the preheat temperatures used in the plateau
235 test for which the SAR equivalent dose is measured.

236 The determinations of the SAR equivalent doses were done using the growth curve as shown
237 in Fig. 6. The average values and their standard errors (it must be multiplied by 2.12 to get the
238 95% confidence interval) are reported Table 2. For each sample, equivalent dose is measured
239 on nine aliquots as well as the dose recovery value.

240 It can be noted that the preheat temperature differs slightly from one sample to another and
241 lies between 250 °C and 280 °C a range where both the recycling ratio is close to 1 and
242 equivalent dose is not dependent on temperature as in Fig. 7 The more frequent value is 260
243 °C.

244 For all aliquots (equivalent dose, recovery dose, etc.) this curve is best fitted with the sum of a
245 saturating exponential and a linear term function (Wintle and Murray, 2006). Calculation of
246 the extrapolated dose has been computed without taking into account the recycling point. This
247 calculation is achieved by using data analysis software developed in our laboratory. The
248 growth curve model is fitted to the experimental data using a Levenberg-Marquardt algorithm,
249 giving the same weight to each data point. The example in Fig. 6 (HAV2 P5-4) is
250 representative of the luminescence characteristics exhibited by our samples. All samples have
251 a natural signal that intersects with the beginning of the linear region of the growth curve; this
252 corresponds to a dose level where saturation is sufficiently low to allow interpolation. It can
253 be noted that curves of natural and regenerated OSL signals have the same shape and are
254 indistinguishable.

255 The dose recovery experiments indicate that the SAR protocol is able to measure within 4% a
256 laboratory dose given prior to any heat treatment. These criteria and the fulfilment of the
257 usual tests provide strong evidence for that the samples are suited for dating with the SAR
258 protocol.

259 Annual dose rates were determined using U, Th and K concentrations of the sediment, its
260 water content and an estimate of the cosmic contribution. These concentrations were
261 measured on a sample representing a zone of ca 30 cm of sediment around the OSL sample as
262 described above. Prior to gamma spectroscopy, the sediment was dried (3 days, 105 °C).
263 Around 10 g of sample was kept at least a week in a sealed tube (100 mm, 15 mm diameter).
264 Measurements lasting ca 24 h. were performed in the *Laboratoire Souterrain de Modane*
265 (CNRS-CEA) where the influence of cosmic rays is drastically limited. We used a very low
266 background GeHP detector whose gain is calibrated with the AIEA standards (RGTh and
267 RGU) for U and Th families and a KCl reference for K activity. Concentrations are

268 summarized in Table 3. Standard errors (1σ) quoted in this table reflect the counting statistics
269 with no appreciable contribution of the AIEA standard uncertainties (IAEA 1987). Within the
270 precision of the gamma measurements the mass activities of the elements of the U and Th
271 decay chains show that all samples are in radioactive equilibrium (for detailed radionuclides
272 activity see supplementary Table 1). Concentrations of U, Th and K were calculated using the
273 specific activities of ^{234}Th , ^{228}Ra and ^{40}K respectively.

274 To quantify the effect of moisture on the annual dose rates we used the water saturation
275 content (Aitken 1985). This parameter has been measured (Table 3) for each sample. A batch
276 of ca 50 g is soaked in water for over 24 h, then drained for ca 6 hours (wet weight) checking
277 when the weight is stabilised, then the batch is dried for 1 day at 105 °C (dry weight).
278 Saturation content is the difference between the wet weight and the dried weight divided by
279 the dried weight. Incidence of moisture is calculated by assuming the mean water content of
280 the sediment since its deposition lies between 60 to 100% of the saturated value determined in
281 the laboratory. We further assume this mean has a uniform distribution in this interval, thus
282 following the recommendation of the Joint Committee for Guides in Metrology (JCM100
283 2008; §4.3.7). This can be represented by the factor 0.80 ± 0.12 ; the associated uncertainty
284 being compatible with the Gaussian error propagation law. This method, using saturation
285 content, has been preferred because the natural water content could not be determined reliably
286 for all the samples as some were not properly sealed on the field.

287 Alpha radiations having a reduced luminescence effectiveness (Aitken 1985), an a -value for
288 each sample was determined as follows. The L_x/T_x obtained after a calibrated alpha
289 irradiation was compared to the L_x/T_x obtained after a calibrated beta irradiation (test dose
290 for T_x and preheat parameters being the same as those of the SAR protocol). The alpha
291 particle flux intercepted by the sample delivers a dose to the sample. The alpha dose rate of
292 the source is calibrated for the fixed geometry of irradiation described in the introduction of
293 this chapter. Initially calibration uses the number of particles by seconds and has been
294 converted into a radiation dose (0.1134 ± 0.0028 Gy/s) that includes small corrections for
295 particles inclinations and incident energies (Guérin, 1982; Valladas and Valladas, 1982;
296 Aitken 1983, 1985). Eventually, the sample deposit density was checked and corrections to
297 the a -value were applied when the density differs from 1 mg/cm^2 .

298 The measured a -value varies from 0.039 to 0.045 (Table 3) with a mean of 0.042; close to the
299 0.039 a -value mean determined by GLSL (green light stimulated luminescence) on fine grains
300 quartz extracts from sediments (Rees-Jones and Tite 1997).

301 Annual dose rates were calculated using data in Tables 2 and 3 and the last revised conversion
302 factors (Guérin *et al.*, 2011). The contribution of cosmic rays to the dose rate was calculated
303 using the depth from the surface (Table 3) and a sediment density of 2 (Prescott and Stephan
304 1982; Prescott and Hutton 1994).

305

306 *ESR/U-Series dating*

307 Two horse teeth found in two different archaeological levels (units 6a and 12 respectively)
308 were sampled for ESR/U-series analyses. The teeth were analysed according to the protocol
309 and parameters described in Bahain *et al.* (2015) (Table 4).

310 Enamel layers have been separated then cleaned with a dental drill in order to eliminate any
311 contamination and the external alpha contribution. The thickness of the removed part on each
312 enamel side (Table 4) has been taken into account in the beta contribution calculation
313 (Brennan *et al.*, 1997). The enamel sample was then ground and sieved, and the 100-200 μm
314 fraction was split into ten aliquots. Nine of them were irradiated using a ^{60}Co gamma source
315 (CEA Saclay, France) at the following doses: 34, 55, 85, 137, 228, 3271, 586, 937 and 1475
316 Gy. ESR intensities (I) of the ten aliquots were then measured using a Bruker EMX ESR
317 spectrometer and equivalent doses D_E were extrapolated from the experimental data using a
318 single saturation exponential function (Duval and Grün 2016) with Microcal *Origin Pro 8*
319 software (weighting by $1/I^2$).

320 Uranium content of the dental tissues (without any preparation) was estimated by gamma
321 spectrometry measurements using a low background GeHP gamma detector (for 1 to 8 days
322 according to the amount and activities of the considered samples) at the *Muséum National*
323 *d'Histoire Naturelle* at Paris, France. The tissues were then analysed by U-series using a
324 Neptune MC-ICPMS device at Nanjing Normal University, China following the chemical
325 protocol of Shao *et al.* (2015). Eventual Ra and Rn losses from the dental tissues were also
326 estimated from cross-checked gamma and ICP data (Bahain *et al.*, 1992).

327 Activities of natural radionuclides from associated sediments were also determined by gamma
328 spectrometry (usually with measurements for a couple of days) and *in situ* gamma
329 measurements were performed in the two dated levels (6 and 3 measurements for US6 and
330 US12 respectively) using a Canberra Inspector 1000 spectrometer by the threshold technique
331 (Mercier and Falguères, 2007). Data obtained from the two sets of measurements (including
332 for OSL samples gamma dosimetry) are very homogeneous for each dated level. As for OSL,
333 annual dose rates were determined using U, Th and K concentrations of the sediment directly

334 associated with the tooth samples on 100 g sediment boxes in a similar manner to that used
335 for OSL samples. The water contents determined during the OSL study for the sediments from
336 the two considered units were used for the age calculation. As for the OSL study, the
337 contribution of cosmic rays to the dose rate was calculated using the depth from the surface
338 and a sediment density of 2. Annual dose rates were calculated using an alpha efficiency (k-
339 value) of 0.13 ± 0.02 according to Grün & Katzenberger-Appel (1994) and the last revised
340 conversion factors (Guérin *et al.*, 2011).

341

342 **4) Results**

343 *Radiocarbon*

344 The ^{14}C results obtained for the eight analysed samples of Havrincourt are given in Table 5
345 (calibrations according to IntCal13 curve; Reimer *et al.*, 2013). Concerning the samples
346 carried out from the archaeological level Hav2-N2, only two bones provided dating estimates,
347 the other analyses failed due to low collagen yields. The ^{14}C ages of these two samples are
348 27020 ± 140 BP and 28100 ± 180 BP and they therefore place this Upper Palaeolithic level
349 into the late Aurignacian or early Gravettian periods, despite the absence of typical pieces in
350 the lithic assemblage.

351 Several rodent bones samples recovered in burrows of unit 7 were also dated by ^{14}C at 40100
352 ± 370 BP and 42090 ± 380 BP, i.e. between 43 and 46 ka cal BP. This age postdates the unit 7
353 sediment deposition and corresponds to a period of climatic improvement prior to the cold
354 event represented by the F5 ice wedge formation.

355

356 *OSL*

357 Table 6 shows the optical ages of different Havrincourt profiles from the two sectors. The
358 first, HAV1 P1, is dated at high resolution using 10 samples distributed on the profile. Ages
359 span from 67.6 ± 3.9 ka to 28.9 ± 1.9 ka. Above the HAV1-P1-7 sample, all ages obtained are
360 in good accordance with stratigraphic order. As fossilised burrows are frequent in this zone,
361 the underestimated age of HAV1-P1-7 could be explained by an *in situ* contamination due to
362 the occurrence of a burrow filled with younger sediment.

363 Five ages have been measured in the HAV2-P5 profile. They span the interval between $61.7 \pm$
364 4.0 and 28.4 ± 1.8 ka. As for the HAV1 profile, they follow the expected stratigraphic order.
365 In this profile, two ^{14}C ages have been measured on 2 mammal bones from the Hav2-N2
366 archaeological level corresponding to HAV2-P5-4. In Unit 6a, the OSL age of 34.9 ± 2.3 ka is

367 in agreement with the ^{14}C ages (27020 ± 140 BP and 28100 ± 180 BP), indicating that the
 368 parameters used in the SAR protocol and for dosimetry calculations lead to age determination
 369 with no major bias. Evidence for small bias is given by the ^{14}C age (ca 46 ka calibrated) of
 370 marmot and gopher skeletons found in burrows from unit 7, which are younger than the
 371 HAV2 P5-5 age (51.5 ± 3.2 ka) located at the top of unit 7.

372

373 *ESR/U-Series*

374 Table 7 shows the calculated ESR/U-series ages (US model, Grün et al., 1988 and AU model,
 375 Shao et al., 2012), various dose-rate contributions and the uranium uptake parameters for each
 376 tooth. The choice of the U-uptake model that was applied is not arbitrary, but constrained by
 377 the analytical data (isotopic ratios, D_E and d_a) and restricted to only one model. The dose
 378 conversion factors of Guérin et al. (2011) and a water content of $33 \pm 4\%$, corresponding to
 379 the values determined on OSL samples, was used for the age calculation. The results are 34.0
 380 ± 2.0 ka and 67.0 ± 4.0 ka for archaeological levels Hav2-N1 (unit 6a) and Hav2-N2 (unit 12)
 381 respectively and are in agreement with corresponding OSL HAV2-P5-4 and HAV1-P1-9 ages.

382

383 **5) Bayesian treatment**

384 In order to provide a more informed and robust view of the chronology of the sequence, a
 385 Bayesian hierarchical model was built with *ChronoModel* software (version 1.5) (Vibet et al
 386 2016). *ChronoModel* is free software that is intended to provide tools for constructing
 387 chronologies in archaeology from several dating results (^{14}C , OSL etc) and temporal
 388 constraints (Lanos et al. 2015, 2017).

389 The Event model combines dates that are assumed to be contemporaneous by introducing an
 390 error term that may correct for unknown errors:

$$391 \quad t_i = D + \epsilon_i, \quad (\text{Eq. 1})$$

392 where ϵ_i represents the error that might exist between the date t_i obtained from the
 393 archeometric method and the date of interest D. The distribution of ϵ_i is a Gaussian
 394 distribution with zero mean and variance σ_i^2 . The choice of a symmetric distribution is
 395 justified by the fact that the date t_i may be older or younger than the date of interest (See
 396 Lanos and Philippe 2017).

397

398 *Modeling*

399 The aim of the modeling is to obtain precise ages for the Paleolithic levels and the period of
400 deposition of the associated geological layers. The observations used for these estimations are
401 the date estimates obtained from the different dating techniques and the stratigraphic order,
402 which forms the basis of the prior information for the model.

403 At Havrincourt, the chronology is mainly based on OSL measurements. 17 OSL samples were
404 taken from two different sectors and from several units (from unit 12 to unit 2) that were
405 observed in both sectors. The OSL age corresponds to the date of the last exposure to the light
406 of the quartz grains, so it refers to the deposition time of the different units. In the modeling
407 with *ChronoModel*, each event is associated to only one OSL measurement, and the event
408 date is the last exposure time of the sample to light. All events from the same layer are
409 gathered in a phase in order to estimate the period of deposition of the associated layer.
410 Hence, 8 groups of dates were defined in the Havrincourt sequence, corresponding to 8 dated
411 units at the site (Table 6 and Figure 8). Moreover, temporal order can be imposed between
412 these events taking into account the geological and the pedostratigraphic information (Figure
413 8).

414 Other samples were collected and dated from the site (Tables 5 and 7) as mentioned above:
415 two horse teeth from Units 12 and 6a dated by ESR/U-series and mammal bones (Units 7 and
416 6) dated by radiocarbon. These dating techniques date the death of the animal that lived on
417 (for the horses) or into (for the rodents) the sediment in which they were found. According to
418 geological and pedostratigraphic information, these dates comprise prior information, and are
419 included in the model as *Terminus Ante Quem / Terminus Post Quem* (Figure 8). In addition,
420 we consider that the two TL dates constrain US12 as two *Termini Post Quem*. These TL dates
421 can therefore be older than the estimated date of the start of US12.

422

423 *Computational aspects*

424 Markov Chain Monte Carlo (MCMC) algorithms are implemented to approximate the
425 posterior distribution of the dates. To assess the agreement between the posterior distributions
426 and the numerical approximations, three Markov chains were run in parallel. For each chain,
427 1 000 iterations were used during the Burn-in period, 20 batches of 500 iterations were used
428 in the Adapt period, 100 000 iterations were drawn in the Acquire period but only 1 out of 10
429 were kept in order to break the correlation structure.

430 From the analysis of the history plots, all Markov chains reach their equilibrium before the
431 Acquire period. This is confirmed by the Gelman-Rubin criterion. Indeed it is equal to 1 (this
432 is the expected value to confirm that all of the Markov chains reached equilibrium). The

433 autocorrelations of the three Markov chains are not significant, meaning the rate of subsample
434 (1 over 10) is enough. We generated acceptable samples for the posterior distribution.
435 Gathering the three chains, a total of 30 000 iterations was collected in order to give reliable
436 estimations of the posterior distribution for each parameter.

437

438 **Results**

439 The Bayesian chronological approach implemented in *Chronomodel* is based on a hierarchical
440 classification called “*event model*” (see Lanos and Philippe (2017) for the description of the
441 model) The main idea is to embed all the dates in “*event model*” to allow individual errors
442 between the target date and the dates obtained by different chronometric techniques.

443 The main interest of this approach is to provide a robust model with respect to outlier dates
444 (dates that are not properly related to the target date) or temporal order inversions. To assess
445 the suitability of the model, we analysed the posterior distributions of the standard deviations
446 of these error terms. For all of the dates, the maximum *a posteriori* probability estimate is
447 smaller than 2,000 years. These small values (with respect to the estimated ages, between
448 20,000 and 130,000 years) indicate the good fit between the model and the data.

449 In Figure 9 we show the posterior distributions of the minimum and maximum of each group
450 of dates defined in Figure 7 and corresponding to the different stratigraphic units. The
451 minimum and maximum values provide an estimation of the beginning and end of the
452 sediment deposition of the unit associated with the group of dates. Only one date is associated
453 with the Hav2-N1 archaeological level, US10 and US5. So, for these three levels, the
454 minimum and the maximum are equal.

455 In Figure S1 the supplementary information is shown which characterizes the different
456 periods. The *time range interval* (Philippe *et al.* 2017) gives an estimation of the period taking
457 into account the uncertainty on the estimation of the beginning and the end. More formally, it
458 corresponds to the shorter interval covering all the dates of the group with 95% probability.
459 The numerical values are summarized in Table S2.

460 The whole data set is stratigraphically coherent. We can observe, however, that for the
461 probability distributions associated with layers US2 and US12 (Figure 9), heavy tails are
462 present due to the lack of prior information for these two periods. Unlike other units, there is
463 no temporal constraint on the beginning of US12 and the end of US2. For the HAV2-N1
464 archaeological level, the age of the analyzed tooth is coherent with the estimated end of
465 deposition of the US 12 sediments, between 74.0 and 61.4 ka, and differs greatly from the
466 flint TL ages. On the other hand, the dates obtained on Hav2-N2 paleontological material are

467 in agreement and provide an interval ranging between 37.0 and 30.4 ka. Lastly, the range
468 derived from the ^{14}C dates of the rodent remains from US7 and from overlying and
469 underlying sediments (US7 and US6, including Hav2-N2 archaeological level) place the
470 deposition of these units during MIS3 as well as during the development of the F5 ice wedge
471 stage.

472

473 **6) Chronoclimatic interpretation of the sequence and regional comparison**

474 The geochronological data obtained at Havrincourt allows us to consider how the sequence
475 compares to the global chronoclimatic subdivisions recently proposed for the Last Glacial
476 loess sequences of northern France and Belgium by Antoine et al. (2016)(Fig. 10)

477

478 *Eemian Last Interglacial and Early-glacial (LPG)*

479 The Weichselian Early-Glacial corresponds to the time interval between the end of the Last
480 Interglacial (Eemian) and the Lower Pleniglacial starting at about 70 ka with the first typical
481 loess deposition. In western Europe, and especially in northern France, the analysis of
482 numerous Early-glacial soil complexes has shown two periods of different duration: A) a long
483 grey-forest soil phase and B) a short steppe soil phase.

484 *Phase A (MIS 5c to 5a)* starts with a first event of erosion and colluvial deposition during the
485 first cold stage directly following the Eemian (MIS 5d \pm 112 ka). These colluvial clayey-silty
486 deposits are then affected by a pedogenesis (BSO Soil) that shows an intermediate facies
487 between the Interglacial Bt horizon and a grey forest soil (Bth). The characteristics of this
488 horizon include clayey to silty-clayey weakly humic stratified coatings, and numerous
489 earthworm bioturbation features, corresponding to a continental climate, which is comparable
490 to that of present-day central Europe. A deep seasonal freeze episode then impacted this
491 horizon during the cold stage at the transition between MIS 5c and 5b (~ 90-88 ka). This
492 episode is followed by the deposition of silty-clayey colluvial deposits reworking the
493 underlying soil horizons in which a new and markedly more humic grey-forest soil
494 pedogenesis develops. This horizon (soil SS1), exhibiting numerous earthworm galleries and
495 chambers, testifies to upbuilding (cumulic) soil formation dynamics during MIS 5a. The SS1
496 soil is then impacted by a deep seasonal frost event and a strong erosional event during the
497 very intense climatic deterioration that marks the end of MIS 5a around 78 ka ago (GS 21).

498

499 *Phase B* (end of MIS 5a ~ 78-70 ka ago) is represented by the formation of isohumic soils
500 (Ah horizons) indicating a markedly more arid environment that is typical of a more arid

501 steppe landscape. This part of the complex (soils SS2 and SS3a&b) is clearly distinguished by
502 the occurrence of the first aeolian deposits. It corresponds in all probability to an expanded
503 response of the continental environments to the short climatic oscillations observed in the
504 Greenland Ice cores between ~ 75 and 70 ka ago (GI 20 and 19).

505 At Havrincourt, the record of the impact of these complex climatic variations is not well
506 preserved and is restricted to unit 14 including only a grey forest soil horizon (unit 14b) and
507 an isohumic soil horizon (14a) overlying the truncated Eemian palaeosoil (unit 15).

508

509 *Weichselian Lower Pleniglacial*

510 Given the OSL and ESR/U-series dating results, field observations (significant erosion,
511 colluvial facies, frost cracks) and sedimentology data (showing increasing wind dynamics),
512 Havrincourt units 13 to 8 are allocated to the initial phases of the Weichselian Lower
513 Pleniglacial and correlated to MIS 4. Unit 13 corresponds to heterogeneous bedded colluvial
514 deposits related to a significant erosion of the former levels including the early-glacial humic
515 soil complex. Even if this unit were not dated in the present work, its geological location in
516 the sequence, by comparison with the other regional records, places its deposition during the
517 Lower Pleniglacial. Above it, the homogeneous and mainly non-calcareous brown silt of unit
518 12 (*Havrincourt brown silt*, HBS) incorporates a strong aeolian component and has been
519 dated to ca 70 ka ago. However, OSL ages of 67.6 ± 3.9 ka and the ESR/U-series age of the
520 tooth recovered from the HAV2-N1 archaeological layer (67.0 ± 4.0 ka), are clearly in
521 agreement with an allocation to Lower Pleniglacial, which is also strongly suggested by the
522 results of the Bayesian model.

523 The top of the Havrincourt brown silt is marked by the development of a very thin
524 hydromorphic horizon (micro-gley) related to the increase of surface moisture and to freeze-
525 thaw processes, then by the deposition of loessic material poor in CaCO_3 (unit 10). After
526 another gley sediment recorded in unit 9, aeolian sedimentation is reinforced by the
527 deposition of a loess deposit showing a constant thickness in all profiles at Havrincourt (unit
528 8), which reflects a significant increase in wind dynamics and a more advanced and intense
529 cold phase with the sedimentation of the first typical carbonated loess of the Last Glacial
530 period ca 60 ka ago.

531 There are numerous similarities between this part of the Havrincourt sequence and other
532 French and Belgian records (Fig. 10), in which the Early-glacial soil complex is overlain by
533 heterogeneous stratified silts and soil lenses capped by a homogeneous brown horizon known
534 as the *Malplaquet Soil* (Haesaerts et al., 1999, in press). The first evidence of loess

535 sedimentation in these sequences always appears above this brown horizon and could
536 correspond to the calcareous loess dated at ca. 65 ka at Harmignies and Nussloch (Antoine et
537 al., 2001; Frechen et al., 2001).

538

539 *Weichselian Middle Pleniglacial*

540 At Havrincourt, as in numerous Northern France loessic sequences, the uppermost Lower
541 Pleniglacial loess is affected by a total decalcification linked to the development of a boreal
542 brown soil, corresponding to a Bw horizon of boreal brown soil (Cambisol / unit 7). The
543 available dates confirm it belonging to the lower half of the Middle Pleniglacial. This brown
544 soil is characterized by numerous large rounded or oval bioturbations (krotovinas: 5 to 15 cm
545 in diameter) at the site resulting from burrowing by small mammals (marmots, ground
546 squirrels, Arvicolidae, steppe polecat). The large mammal assemblage found in this horizon
547 includes large herbivores such as horse, woolly rhinoceros and mammoth (Antoine et al.,
548 2014). According to ^{14}C ages obtained from rodent bones from krotovinas, the surface of the
549 soil where these mammals have been living is dated at about 42-46 ka BP.

550 A first network of large V-shaped frost cracks of the ice-wedge type (≈ 1.5 m deep) then
551 opens at the top of this soil horizon (F-5). The formation of the upper part of the *Havrincourt*
552 *soil complex* (unit 6) begins with a new thin loess deposit mostly trapped in the ice-wedge
553 casts of the F5 level. This is followed by at least two phases of soil formation corresponding
554 to a hydromorphic arctic brown to arctic meadow soil horizon, strongly structured by the
555 freeze-thaw processes connected with the ice-wedge level F-4. Given the available dates, the
556 Upper Palaeolithic human occupation Hav2-N2, preserved in its upper part, could therefore
557 date to ca 31-32 ka ago. The early Gravettian cultural attribution of the associated lithic
558 industry seems supported by the recent discovery 70 km southwestwards of the Renancourt-1
559 site, close to Amiens, which contains a similar industry in association with several female
560 figurines (“Venus”) in chalk. This was dated by OSL and ^{14}C to ~ 27 -28 ka cal BP (Antoine et
561 al., 2014b), in the same time range as the Havrincourt Hav2-N2 level.

562

563 *Weichselian Upper Pleniglacial*

564 Overlying this brown soil complex are sediments dating to the Upper Pleniglacial. This is
565 evidenced at Havrincourt and in the wider regional profiles by a marked acceleration of loess
566 sedimentation rates. A tundra gley (unit 5) is the first unit allocated to this period. The
567 formation of this horizon results from seasonal water saturation of the active layer of a

568 permafrost indicated by its connection with the large ice-wedge casts of the main network (F-
569 4). Our results date the tundra gley formation to ca 31 ka ago.

570 Later, the fossilization of this horizon and of the network of large ice-wedge casts indicates
571 that loess deposition occurs in a dry and cold environment. The peak of this first loess unit of
572 the Upper Pleniglacial is underlain by a thick and complex tundra gley (unit 3) which is
573 subdivided into two horizons separated by a thin bed of calcareous loess, mainly preserved
574 within an ice-wedge cast (network F-3). The infilling of this F-3 network shows local
575 laminations and cross stratification indicating a phase of intense permafrost thawing during an
576 episode of interstadial warming (Antoine et al., 2014a).

577 The upper horizon of the tundra gley is associated with a large ice-wedge cast network with
578 homogeneous loess (unit 2) infilling $\approx 0.3 \times 1.2$ m deep (network F-2), systematically
579 superimposed on the previous level (F-3). As there is not upper constraint for this unit 2, the
580 Bayesian age estimate for the range is quite large but the OSL date (28.4 ± 1.8 ka) available
581 from this loess shows that this part of the sequence accumulated very rapidly, possibly over a
582 span of ca. 2 to 3 ka at the most, between 26-27 and 28-29 ka ago.

583

584 **6) Conclusions**

585 The OSL, ^{14}C , TL and ESR/U-series results from Havrincourt represent the first reliable set of
586 dating results for the Upper Pleistocene loess-palaeosol sequences of northern France. The
587 Bayesian modelling allows us to test the reliability of the dates and age estimates with respect
588 to the stratigraphic constraints. The following observations can be drawn:

589 - For the first time, evidence has been found for the deposition of a typical calcareous loess
590 bed during the Lower Pleniglacial at about 70-65 ka ago.

591 - Accurate dating of the youngest brown soil horizon (arctic brown soil) marks the end of the
592 Middle Pleniglacial by ca 38-33 ka BP, as it does for all European loess sections,

593 - Evidence has been obtained for the deposition of a very homogeneous calcareous loess bed
594 during the major climatic degradation (centered on 30.5 ka BP) in the reference
595 palaeoclimatic records from Greenland and North Atlantic marine cores. This suggests that
596 the Heinrich 3 event is coeval to the onset of a major climatic modification in the European
597 continent, in terms of wind regime and land erosion.

598 - Accurate dates have been obtained for a first succession of permafrost events each marked
599 by the formation of large polygonal networks of ice-wedge casts with pure loess infilling
600 between 26 and 29 ka BP.

601 - We obtained dates for four levels of human occupation including an Upper Palaeolithic level
602 through the ^{14}C dating of large mammal bones and ESR/U-series dating of large mammal
603 teeth.

604

605 In the near future, a new rescue archaeological campaign planned on the area of Havrincourt
606 and in the surrounding loess zone crossed by the Seine-Nord-Europe Canal Project will allow
607 us to refine these results and provide new data for loess and Palaeolithic research in western
608 Europe.

609

610 **Acknowledgements**

611 The authors thank the French Institute for Rescue Archaeological Research (INRAP Nord-
612 Pas-de-Calais-Picardie / Coordination Canal Seine Nord-Europe) for the financial support to
613 OSL and ESR/U-series dating of the Havrincourt sequence. We thank also gratefully two
614 anonymous referees and Tom Higham, QG editor, for their constructive comments, helps in
615 English writing and proposals that are allowed to improve greatly the manuscript.

616

617 **References**

- 618 Adamiec, G., Aitken, M., 1998. Dose-rate conversion factors: update. *Ancient TL*, 16, 37-50.
- 619 Aitken, M.J., 1983. Alpha particle effectiveness: numerical relationship between systems.
620 *Ancient TL*, 3, 22-25.
- 621 Aitken, M.J., 1985. *Thermoluminescence Dating*, Academic Press, London.
- 622 Antoine, P., 1991. Nouvelles données sur la stratigraphie du Pléistocène supérieur de la
623 France septentrionale, d'après les sondages effectués sur le tracé du TGV Nord.
624 *Publications du Centre d'Études et de Recherches Préhistoriques*, 3, 9-20.
- 625 Antoine, P., 1994. The Somme Valley terrace system (Northern France); a model of river
626 response to quaternary climatic variations since 800 000 BP. *Terra-Nova*, 6, 453-464.
- 627 Antoine, P., 2012. Thermokarst processes and features from west-european loess series: new
628 evidences for rapid climatic warning events during the Last Glacial. *Quaternary*
629 *International*, 21, 279-280.
- 630 Antoine, P., Lautridou, J.-P. Sommé, J., Auguste, P., Auffret, J.-P., Baize, S., Clet-Pellerin, M.,
631 Coutard, J.-P., Dewolf, Y., Dugué, O., Joly, F., Laignel, B., Laurent, M., Lavollé, M.,
632 Lebret, P., Lefebvre, D., Lécolle, F., Limondin-Lozouet, N., Munaut, A.-V., Ozouf, J.-C.,

- 633 Quesnel, F., Rousseau, D.-D., 1998. Les formations quaternaires de la France du Nord-
634 Ouest : limites et corrélations. *Quaternaire*, 9, 227-241.
- 635 Antoine, P., Rousseau, D.-D., Lautridou, J.-P., Hatté, C., 1999. Last interglacial-glacial
636 climatic cycle in loess-paleosol successions of north-western France. *Boreas*, 28, 551-563.
- 637 Antoine, P., Rousseau, D.-D., Zöller, L., Lang, A., Munaut, A.V., Hatté, C., Fontugne, M.,
638 2001. High resolution record of the last Interglacial-glacial cycle in the Nussloch loess-
639 palaeosol sequences, Upper Rhine Area Germany. *Quaternary International*, 76-77, 211-
640 229.
- 641 Antoine, P., Auguste, P., Bahain, J.-J., Coudret, P., Depaepe, P., Fagnart, J.-P., Falguères, C.,
642 Fontugne M., Frechen., Hatté, C., Lamotte, A., Laurent, M., Limondin-Lozouet, N., Locht,
643 J.-L., Mercier, N., Moigne, A.-M., Munaut, A.-V., Ponel, P., Rousseau, D.-D., 2003a.
644 Paléoenvironnements pléistocènes et peuplements paléolithiques dans le bassin de la
645 Somme (nord de la France). *Bulletin de la Société préhistorique française*, 100, 5-28.
- 646 Antoine, P., Bahain, J.-J., Debenham, N., Frechen, M., Gauthier, A., Hatté, C., Limondin-
647 Lozouet, N., Locht, J.-L., Raymond, P., Rousseau, D.-D., 2003b. Nouvelles données sur le
648 Pléistocène du Nord du Bassin Parisien : les séquences loessiques de Villiers-Adam (Val
649 d'Oise, France). *Quaternaire*, 14, 219-235.
- 650 Antoine, P., Rousseau, D.-D., Moine, O., Kunesch, S., Hatté, C., Lang, A., Zöller, L., 2009.
651 Evidence of rapid and cyclic eolian deposition during the Last Glacial in European loess
652 series (Loess Events): the high-resolution records from Nussloch (Germany). *Quaternary*
653 *Science Reviews* 28, 2955-2973.
- 654 Antoine, P., Goval, E., Jamet, G., Coutard, S., Moine, O., Herisson, D., Auguste, P., Guérin,
655 G., Lagroix, F., Schmidt, E., Robert, V., Debenham, N., Meszner, S., Bahain, J.-J. 2014a.
656 Les séquences loessiques pléistocène supérieur d'Havrincourt (Pas-de-Calais, France) :
657 stratigraphie, paléoenvironnement, géochronologie et occupations paléolithiques.
658 *Quaternaire* 25 (4), 321-368.
- 659 Antoine P., Locht J.-L., Limondin-Lozouet N., Auguste P., Bahain J.-J., Fagnart J.-P.,
660 Debenham N. & Ducrocq T. (2014b) – Quaternary geoarcheology and Prehistory: the
661 model of the Somme valley (France) and the neighbouring regions. In Arnaud-Fassetta G.
662 & Carcaud N. (Eds.) *French geoarchaeology in the 21st century*, CNRS éditions, Paris, 71-
663 86.
- 664 Antoine, P., Coutard, S., Guérin, G., Deschodt, L., Goval, E., Locht, J.-L., Paris, C., 2016.
665 Upper Pleistocene loess-palaeosols records from Northern France in the European context:

- 666 environmental background and dating of the Middle Palaeolithic. *Quaternary International*
667 411, 4-24.
- 668 Bahain, J.-J., Falguères, C., Dolo, J.-M., Antoine, P., Auguste, P., Limondin-Lozouet, N.,
669 Loch, J.-L., Tuffreau, A., 2010. ESR/U-series dating of teeth recovered from well-
670 stratigraphically age-controlled sequences from Northern France. *Quaternary*
671 *Geochronology*, 5, 371-375.
- 672 Bahain, J.-J., Falguères, C., Laurent, M., Dolo, J.-M., Shao, Q., Auguste, P., Tuffreau, A.,
673 2015. ESR/U-series dating of faunal remains from the paleoanthropological site of Biache-
674 Saint-Vaast (Pas-de-Calais, France). *Quaternary Geochronology*, 30, 541-546.
- 675 Bahain, J.-J., Yokoyama, Y., Falguères, C., Sarcia, M.N., 1992. ESR dating of tooth enamel: a
676 comparison with K-Ar dating. *Quaternary Science reviews*, 11, 245-250.
- 677 Bøtter-Jensen, L., Bulur, E., Murray, A.S., Poolton, N.R.J., 2002. Enhancements in
678 luminescence measurement techniques. *Radiation Protection Dosimetry*, 101, 119-124.
- 679 Brennan, B.J., Rink, W.J., McGuirl, E.L., Schwarcz, H.P., Prestwich, W.V., 1997. Beta doses
680 in tooth enamel by “One Group” theory and the Rosy ESR dating software. *Radiation*
681 *Measurements*, 27, 307–314.
- 682 Deschodt, L., Barbier, P., Djemmali, N., Drwila, G., Feray, P., Teheux, E., 1998. Onnaing,
683 Usine Toyota, Rapport des sondages archéologiques profonds. 06/98 Villeneuve d'Ascq.
684 Institut National Archéologiques préventives, Rapport de sondage, Direction Régionale des
685 Affaires Culturelles du Nord-Pas-de-Calais, Service Régional de l'Archéologie, 66 p.
- 686 Duller, G.A.T., 2003. Distinguishing quartz and feldspar in single grain luminescence
687 measurements. *Radiation Measurement*, 37, 161-165.
- 688 Duval, M., Grün, R., 2016. Are published ESR dose assessments on fossil tooth enamel
689 reliable? *Quaternary Geochronology*, 31, 19-27.
- 690 Frechen, M., Schweitzer, U., Zander, A., 1996. Improvements in sample preparation for the
691 fine grain technique. *Ancient TL*, 14, 15–17.
- 692 Frechen, M., van Vliet-Lanoë, B., van den Haute, P., 2001. The Upper Pleistocene loess
693 record at Harmignies/Belgium-high resolution terrestrial archive of climate forcing.
694 *Paleogeography, Paleoclimatology, Paleoecology* 173, 175-195.
- 695 Goval, E., Hérison, D. (dir). (submitted). Les occupations moustériennes et gravettiennes
696 d'Havrincourt (Pas-de-Calais, France). *Approches taphonomiques, techno-économique,*
697 *fonctionnelle et Spatiale des assemblages. ERAUL.*
- 698 Grün, R., Katzenberger-Apel, O., 1994. An alpha irradiator for ESR dating. *Ancient TL*, 12,
699 35–38.

- 700 Grün, R., Schwarcz, H.P., Chadam, J.M., 1988. ESR dating of tooth enamel: coupled
701 correction for U-uptake and U-series disequilibrium. *Nuclear Tracks and Radiation*
702 *Measurements*, 14, 237-241.
- 703 Guérin, G., 1982. Evaluation des débits annuels de dose utilisés pour la datation des coulées
704 volcaniques. *PACT J*, 6, 179-187.
- 705 Guérin, G., Mercier, N., Adamiec, G., 2011. Dose-rate conversion factors: update. *Ancient TL*,
706 29, 5–8.
- 707 Guérin, G., Valladas, H., 2014. Cross-calibration between beta and gamma sources using
708 quartz OSL: Consequences of the use of the SAR protocol in optical dating. *Radiation*
709 *Measurements*, 68, 31-37.
- 710 Haesaerts, P., 1985. Les loess du Pléistocène supérieur en Belgique. Comparaisons avec les
711 séquences d'Europe centrale. *Bulletin de l'Association Française pour l'Etude du*
712 *Quaternaire*, 22-23 (2-3), 105-115.
- 713 Haesaerts, P., 2000. Pedosedimentary evolution of the last interglacial and early glacial
714 sequence in the European loess belt from Belgium to central Russia. *Netherlands Journal*
715 *of Geosciences*, 79, 313-324.
- 716 Haesaerts, P., Borziac, I., Chekha, V.P., Chirica, V., Drozdov, N.I., Koulakovska, L., Orlova,
717 L.A., van der Plicht, J., Damblon, F., 2010. Charcoal and wood remains for radiocarbon
718 dating Upper Pleistocene loess sequences in Eastern Europe and Central Siberia.
719 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 29 (1-2), 106-127.
- 720 Haesaerts, P., Borziac, I., Chirica, V., Damblon, F., Koulakovska, L., Van der Plicht, J., 2003.
721 The East-Carpathian loess record: a reference for the Middle and Late Pleniglacial
722 stratigraphy in Central Europe. *Quaternaire* 14 (3), 163-188.
- 723 Haesaerts P., Damblon F., Gerasimenko N., Spagna P., Pirson S., 2016. The Late Pleistocene
724 loess-palaeosol sequence of Middle Belgium. *Quaternary international*, 411 A, 25-43.
- 725 Haesaerts, P., Juvigné, E., Kuyl, O., Mùcher, H., Roebroeks, W., 1981. *Compte rendu de*
726 *l'excursion du 13 Juin 1981, en Hesbaye et au Limbourg Néerlandais, consacrée à la*
727 *chronostratigraphie des loess du Pléistocène supérieur. Annales de la Société Géologique*
728 *de Belgique* 104, 223-240.
- 729 Haesaerts, P., Mestdagh, H., Bosquet, D., 1999. The sequence of Remicourt (Hesbaye-
730 Belgium): new insights on the pedo and chronostratigraphy of the Rocourt Soil. *Geologica*
731 *Belgica* 2 (3/43), 5-27.

- 732 Haesaerts, P., Van Vliet-Lanoë, B., 1974. Compte-rendu de l'excursion du 25 mai 1974
733 consacrée à la stratigraphie des limons aux environs de Mons. Annales de la Société
734 Géologie et de Paléontologie 978, 547-560
- 735 Hérissou, D., Goval, E., 2013. Du Paléolithique inférieur au début du Paléolithique supérieur
736 dans le Nord de la France : lumière sur les premières découvertes du Canal Seine-Nord
737 Europe. Notae Praehistoricae, 33, 91-104.
- 738 Hérissou, D., Coutard, S., Goval, E., Loch, J.-L., Antoine, P., Chantreau, Y., Debenham, N.,
739 2016. A new key-site for the end of the Lower Palaeolithic and the onset of the Middle
740 Palaeolithic at Etricourt-Manancourt (Somme, France). Quaternary International 409 (B),
741 73-91.
- 742 IAEA, 1987. Preparation of Gamma-ray Spectrometry Reference Materials RGU-1, RGTh-1
743 and RGK-1 Report - IAEA/RL/145, Vienna.
- 744 JCGM 100, 2008. Evaluation of measurement data - Guide to the expression of uncertainty in
745 measurement.
- 746 Juvigné, E., Tallier, E., Haesaerts, P., Pirson, S., 2008. Un nouveau stratotype du Téphra de
747 Rocourt dans la carrière de Romont (Eben/Bassenge, Belgique). Quaternaire 19 (2), 133-
748 139.
- 749 Lang, A., Lindauer, S., Kuhn, R., Wagner, G.A., 1996. Procedures used for optically and
750 infrared stimulated luminescence dating of sediments in Heidelberg. Ancient TL, 14, 7–11.
- 751 Lanos P., Philippe A. (2015) Event model: a robust Bayesian tool for chronological modeling.
752 <hal-01241720> <https://hal.archives-ouvertes.fr/hal-01241720>
- 753 Lanos P., Philippe A. (2017) Hierarchical Bayesian modeling for combining Dates in
754 archaeological context. Journal de la Société Française de Statistique. To appear.
755 <https://hal-insu.archives-ouvertes.fr/insu-01451452/document>
- 756 Lautridou, J.-P., 1985. Le cycle périglaciaire pléistocène en Europe du Nord-Ouest et plus
757 particulièrement en Normandie. Thèse Lettres. Univ. Caen, 908 p.
- 758 Lautridou, J.P., Sommé, J., Heim, J., Puisségur, J.J., Rousseau, D.D., 1985. La stratigraphie
759 des loess et formations fluviatiles d'Achenheim (Alsace) : nouvelles données
760 bioclimatiques et corrélations avec les séquences pléistocènes de la France du Nord-Ouest.
761 Bulletin de l'Association Française pour l'Etude du Quaternaire 22, 125-132.
- 762 Loch, J.-L., Antoine, P., Auguste, P., Bahain, J.-J., Debenham, N., Falguères, C., Farkh, S.,
763 Tissoux, H., 2006. La séquence loessique pléistocène supérieur de Savy (Aisne France):
764 stratigraphie, datations et occupations paléolithiques. Quaternaire, 17 (3), 269-275.

- 765 Loch, J.-L., Antoine, P., Auguste P., Caspar, P., Depaepe, P., Engelmann, A., Frechen, M.,
766 Michel, V., Munaut, A.-V., Révillon, S., Swinnen, C., 2002. Le site de Bettencourt-Saint-
767 Ouen (Somme), cinq occupations du Paléolithique moyen au début de la dernière
768 glaciation. Paris, éd. de la Maison des sciences de l'Homme. Documents d'Archéologie
769 Française, 90, 168 p.
- 770 Loch, J.-L., Antoine, P., Bahain, J.-J., Dwirila, G., Raymond, P., Limondin-Lozouet, N.,
771 Gauthier, A., Debenham, N., Frechen, M., Rousseau, D.-D., Hatté, C., Haesaerts, P.,
772 Metsdagh, H., 2003. Le gisement paléolithique moyen et les séquences pléistocènes de
773 Villiers-Adam (Val d'Oise, France) : Chronostratigraphie, Environnement et Implantations
774 humaines. Gallia Préhistoire, 45, 3-104.
- 775 Loch, J.L., Swinnen, C., Antoine, P., Révillon, S., Depaepe, P., 2002. Le Gisement
776 paléolithique moyen de Bettencourt-Saint-Ouen (Somme). L'Acheuléen dans la vallée de la
777 Somme : données récentes. Publications du Centre d'Etudes et de Recherches
778 Préhistoriques 6, 199-237.
- 779 Loch J.-L., Hérisson D., Goval E., Cliquet D., Huet B., Coutard S., Antoine P., Feray P.,
780 2016. Timescales, space and culture during the Middle Palaeolithic in northwestern France.
781 Quaternary International, 411 A, 129-148.
- 782 Marcy, T., Sellier, N., Devred, V., Dubois, S., 2009. Bourlon, Havrincourt, Graincourt-lès-
783 Havrincourt, Sains-lès-Marquions (Pas-de-Calais). Rapport de diagnostic de la ZD7, Canal
784 Seine-Nord Europe, Institut National de Recherches Archéologiques Préventives, Croix-
785 Molineaux, 116 p.
- 786 Meijs, E.P.M., 2002. Loess stratigraphy in Dutch and Belgian Limburg. Eiszeitalter und
787 Gegenwart 51, 11-130.
- 788 Meijs, E.P.M., 2011. The Veldwezelt site (province of Limburg, Belgium), environmental and
789 stratigraphical interpretations. In: Jagt, J.W.M., Jagt-Yazykova, E.A., Schins, W.J.H. (Eds.),
790 A Tribute to the Late Felder Brothers-Pioneers of Limburg Geology and Archaeology,
791 Netherland Journal of Geosciences, 90 (2-3), 73-94.
- 792 Mercier, N., Falguères, C., 2007. Field gamma dose-rate measurement with a NaI(Tl)
793 detector: re-evaluation of the "threshold" technique. Ancient TL 25, 1-4.
- 794 Moine, O., Antoine, P., Deschodt, L., Sellier, N., 2011. Enregistrements malacologiques à
795 haute résolution dans les loess et les gleys de toundra du pléniglaciaire weichselien
796 supérieur : premiers exemples du nord de la France. Quaternaire, 22 (4), 307-325.

- 797 Moine, O., Rousseau, D.-D., Antoine, P., 2008. Abrupt malacological and lithological changes
798 along the Upper Weichselian loess sequence of Nussloch (Rhine Valley, Germany).
799 Quaternary Research 70, 91-104.
- 800 Murray, A.S., Olley, J.M., 2002. Precision and accuracy in the optically stimulated
801 luminescence dating of sedimentary quartz: a status review. Geochronometria, 21, 1-16.
- 802 Murray, A.S., Wintle, A.G. 2000: Luminescence dating of quartz using an improved single
803 aliquot regenerative-dose protocol. Radiation Measurements, 32, 57-73.
- 804 Murray, A.S., Wintle, A.G., 2003. The single aliquot regenerative dose protocol: potential for
805 improvements in reliability. Radiation Measurements 37, 377–381.
- 806 Philippe A., Vibet M.-A. (2017) Analysis of Archaeological Phases using the CRAN Package
807 ArchaeoPhases.. <hal-01347895v3> [https://halshs.archives-ouvertes.fr/FMPL/hal-](https://halshs.archives-ouvertes.fr/FMPL/hal-01347895v3)
808 01347895v3
- 809 Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contribution to dose rates for luminescence and
810 ESR dating: large depths and long-term time variations. Radiation Measurements, 23, 497-
811 500.
- 812 Prescott, J.R., Stephan, L.G., 1982. The contribution of cosmic radiation to the environmental
813 dose for thermoluminescence dating. PACT, 6, 17-25.
- 814 Rees-Jones, J., Tite, M.S., 1997. Optical dating results for British archaeological sediments.
815 Archaeometry 39, 177-187.
- 816 Rousseau, D.-D., Antoine, P., Hatté, C., Lang, A., Zöller, L., Fontugne, M., Ben Othman, D.,
817 Luck, J.M., Moine, O., Labonne, M., Bentaleb, I., Jolly, D., 2002. Abrupt millennial
818 climatic changes from Nussloch (Rhine Valley, Germany) eolian (loess) records during the
819 Last Glaciation. Quaternary Science Reviews 21, 1577-1582.
- 820 Rousseau, D.-D., Sima, A., Antoine, P., Hatté, C., Lang, A., Zöller, L., 2007. Link between
821 European and North-Atlantic abrupt climate changes over the last glaciation. Geophysical
822 Research Letters 34, 22.
- 823 Sellier, N., 2005. Bapaume, le Petit Moulin, rapport de diagnostic, Inrap Nord-Picardie, 15 p.
- 824 Shao, Q., Bahain, J.-J., Dolo, J.-M., Falguères, C., 2014. Monte Carlo approach to calculate
825 US-ESR ages and their uncertainties. Quaternary Geochronology, 22, 99-106.
- 826 Shao, Q., Bahain, J.-J., Falguères, C., Dolo, J.-M., Garcia, T., 2012. A new U-uptake model
827 for combined ESR/U-series dating of tooth enamel. Quaternary Geochronology, 10, 406-
828 411.

- 829 Shao, Q., Bahain, J.-J., Wang, W., Jin, C., Wang, Y., Voinchet, P., Lin, M., 2016. Combined
830 ESR and U-series dating of early Pleistocene Gigantopithecus faunas at Mohui and Sanhe
831 Caves, Guangxi, southern China. *Quaternary Geochronology*, 30, 524-528.
- 832 Sommé, J., 1975. Les plaines du Nord de la France et leur bordure : étude géomorphologique.
833 Thèse de Doctorat d'État, Université Paris 1 Panthéon-Sorbonne, Paris, 3 vol., 790 p.
- 834 Valladas, H., Valladas, G., 1982. Effet de l'irradiation alpha sur les grains de quartz. *PACT J*,
835 6, 171-178.
- 836 Vallin, L., Masson, B., 2003. Le gisement moustérien d'Hermies. Le Tio Marché. Rapport de
837 fouille programmée, campagne 2002, SRA Nord-Pas-de-Calais, 34 p.
- 838 Vandenberghe, D., 2004. Investigation of the Optically Stimulated Luminescence Dating
839 Method for Application to Young Geological Sediments. PhD thesis. Ghent University, 358
840 pp.
- 841 Wang, X.L., Wintle, A.G., Du, J.H., Kang, S.G., Lu, Y.C., 2011. Recovering laboratory doses
842 using fine-grained quartz from Chinese loess. *Radiation Measurements*, 46, 1073-1081.
- 843 Vibet M.-A., Philippe A., Lanos P., Dufresne P. (2016) ChronoModel V1.5 User's manual.
844 www.chronomodel.fr.
- 845 Wintle, A.G., Murray, A.S., 2006. A review of quartz optically stimulated luminescence
846 characteristics and their relevance in single-aliquot regeneration dating protocols.
847 *Radiation Measurements*, 41, 369–391.
- 848

849 **Figure caption**

850 **Figure 1.** Location of the Havrincourt site in the European Loess belt (according to Antoine et
851 al., 2003a, modified). 1: Loess (>4m) 2: Loess (<4m) 3: Sandy loess

852 **Figure 2.** Location and view of the Havrincourt excavation area and location of the sampled
853 profiles (after Antoine et al., 2014, modified).

854 **Figure 3.** Stratigraphy and litho-chronological interpretation of the Havrincourt sequence
855 (after Antoine et al., 2014, modified).

856 **Figure 4.** Lithic industry of Havrincourt. 1-4: Middle Palaeolithic pieces: 1 & 2 - Hav.1-N3 –
857 Large Levallois flakes; 3. Hav.2-N0 – Levallois point; 4. Hav.2- N1 - Levallois core ; 5.
858 Upper Palaeolithic Hav.2-N2 – Lithic refitting showing the blade production (drawns by Eve
859 Boitard-Bidaut, Inrap)

860 **Figure 5.** Location of the OSL samples on the Havrincourt profiles. Description of the units is
861 in Fig. 3.

862 **Figure 6.** OSL curves of natural (squares) and regenerated quartz (90 Gy, solid line). Dose–
863 response curve of HAV2 P5-4 is fitted with a linear plus saturating exponential function.
864 Recycling ratios are indistinguishable from unity and the growth curve pass very close to the
865 origin. Preheat temperature for this example is 260 °C.

866 **Figure 7.** Preheat plateau test (plain square), recycling ratio of HAV2 P5-1 (open diamond)
867 and additive recovery test (open circles), representative of the quartz behaviour from
868 Havrincourt loesses. Additive recovery test was achieved by adding 85.1 Gy to the natural
869 sample.

870 **Figure 8.** Modeling done with ChronoModel.

871 Black outlined nodes represent an event. The name written into the node is the name of the date associated
872 to this event and the shape corresponds to the used dating method. An arrow between two events
873 symbolizes a temporal relationship, the arrow heading from the oldest event to the youngest one. At
874 Havrincourt, we have considered 25 events, 17 OSL dates, 8 associated to TL/ESR/14C dates, and temporal
875 relationships.

876 Grey outlined node symbolizes a group of events. An arrow between two groups symbolises a temporal
877 relationship, the arrow heading from the oldest group to the youngest one.

878 **Figure 9.** Densities of the minimum and the maximum of each group of dates (here referring
879 to an unit). Results are represented in years before 2016 AD

880 **Figure 10.** Summary pedo-lithostratigraphic sequence for northern France,

881 chronostratigraphy, dating and correlation with Havincourt and Remicourt (Belgium) sites
 882 *Northern France synthetic record units* - 1: surface soil (a: Ap. horizon; b: Bt horizon; c: banded Bt horizon);
 883 2: homogeneous calcareous loess; 3: greyish and lightly humic tundra gley with tongued horizon
 884 (Nagelbeek Hz.); 4: carbonated laminated loess with cryo-desiccation micro-cracks; 5: cryoturbated tundra
 885 gley doublet with intermediary loess (5b); 6: homogeneous calcareous loess; 7: cryoturbated tundra gley Hz.
 886 & large ice-wedges network (F-4); 8: arctic brown soil / or soil complex; 9: sandy silts or calcareous loess;
 887 10: greyish tundra gley horizon; 11: humic horizon / arctic meadow type soil; 12: brown Boreal soil
 888 complex; 13: heterogeneous bedded slope deposits and sandy silts (thermokarst gully infilling); 14:
 889 homogeneous calcareous loess; 15: thin tundra gley doublet (15a-c) including a calcareous loess unit
 890 (15b); 16: homogeneous brownish non calcareous colluvial silts / incipient soil (arctic meadow Hz.); 17:
 891 laminated colluvial deposits reworking soil lenses and soil nodules with frost cracks; 18: brownish-greyish
 892 non-calcareous loess; 19 to 22: steppe-like soils with interstratified unit of local, non-carbonated loess (MS /
 893 20); 23b: grey forest soil on colluviums; 23a: bleached horizon; 24b: clayey colluviums/grey forest soil
 894 (Bettencourt Soil); 24a: bleached horizon; 25b: Bt horizon of brown leached soil (Rocourt/Elbeuf 1); 25a:
 895 bleached horizon; 26: Saalian calcareous loess.

896 *Unit abbreviations - France* (According to Antoine et al, 2016) - ELB1/SDS: Elbeuf 1 / Sourdon soil horizons
 897 (Eemian); BSO: Bettencourt-Saint-Ouen soil horizon; SS1 to SS3b: Saint-Sauflieu soil horizons; HBS:
 898 Havrincourt brown silts - *Belgium* (According to Haesaerts et al, in press) - HS: Harmignies soil horizon
 899 (Eemian); VSG (A&B): Villers-Saint-Ghislain A and B soil horizons; MPS: Malplaquet soil horizon ; SV-HB4:
 900 Les Vaux Soil horizon

901 *Freeze structures* - A: large ice-wedge casts; B: small wedges with soil infilling; C: frost-creep, solifluction,
 902 gelifluction; D : ice-melt channels (thermokarst); E : Large incision features (thermokarst erosion gullies)

903 *Site name abbreviations* - FaV: Fresnoy au Val; SD: Sourdon; BG: Beugnâtre; Herm.: Hermies; Havr.:
 904 Havrincourt; V.A: Villiers-Adam; BsO: Bettencourt-Saint-Ouen; SSL: Saint-Sauflieu.

905 *Archaeological level with TL dating from heated flints (numbers, Locht et al, 2016) and ESR/U-series on teeth*
 906 *and bones (letters, Locht et al, 2006)*- 1) Villiers-Adam : 110 ± 11 ka ; 2) Fresnoy-au-Val: 106.8 ± 7.5 ka ; 3)
 907 Saint-Hilaire-sur-Helpe: 98.9 ± 9.3 ka ; 4) Mauquenchy Low.: 83 ± 7.6 ka, 5); Mauquenchy Upp.: 77.0 ± 7.2 ka
 908 ; 6) Beauvais: 55.6 ± 4 ka; A) Savy low.: 51 ± 3 ka; B) Savy upp.: 30 ± 2 ka.

909

910 **Table caption**

911 **Table 1.** Details of the SAR protocol used in this study (modified from Murray and Wintle
 912 2000). TPH is the preheat temperature determined for each sample using a preheat plateau test
 913 and dose recovery tests. Most frequent value for TPH is 260 °C.

914 (*) The cycle is repeated twice with an IR-stimulation at 50 °C for 44 s between the steps 2-3.

915 **Table 2.** SAR measurements results.

916 **Table 3.** Havrincourt OSL samples. U, Th and K concentrations measured by gamma
917 spectroscopy and parameters used for annual dose rate calculation (Sample depth from the
918 surface; ratio of the water weight at saturation to dry sample weight; alpha efficiency
919 determined using a ^{241}Am calibrated source).

920 **Table 4.** ESR/U-series parameters used for the Havrincourt horse teeth.

921 **Table 5.** C14 dates obtained on fossil bones from Havrincourt (calibrations according to
922 Reimer et al. (2013), IntCal13)

923 **Table 6.** Age results. Annual dose rates are calculated using table 3 data and most recent
924 revised conversion factors (Guérin et al. 2011). Corrections due to moisture are calculated by
925 applying a uniform factor, 0.8 ± 0.12 , to the water saturation level. Uncertainties on
926 equivalent dose include a 1.2% error on the beta source calibration.

927 **Table 7.** ESR/U-series age results for the Havrincourt horse teeth. (a) A k-value of 0.13 ± 0.02
928 was used according to Grün and Katzenberger-Appel (1994); (b) Cosmic dose was estimated
929 from the Prescott and Hutton's data (1994); (c) Uncertainties on the ESR/U-series ages
930 (model US, Grün et al. 1988 or model AU, Shao et al. 2012) were calculated using Monte-
931 Carlo approach (Shao et al.,2014).

932

933 **Supplementary material**

934 **Figure S1.** *Time range interval* for the units succession of Havrincourt. Results
935 are represented in years before 2016 AD. Segments to time range of the phase associated to a
936 level confidence of 95%.

937 **Table S1.** Activity (Bq/kg) of main natural radionuclides of U and Th decay chains of the
938 Havrincourt OSL sediment samples measured by gamma spectroscopy ($^{234}\text{Th1}$ and $^{234}\text{Th2}$
939 correspond to 63.3keV and 92.3 keV gamma emissions respectively).

940 **Table S2.** Time range endpoints for Havrincourt units (at level 95%). Results are represented
941 in years before 2016 AD.

942

Step	OSL measurements	
1	Given dose: 0 (Nat), R1, R2, R3, R4, 0, R1, R1*	
2	Preheat at T_{PH} for 10 s	
3	OSL at 125 °C for 44 s	Lx
4	Test dose 10 Gy	
5	Cutheat 180 °C for 1 s	
6	OSL at 125 °C for 44 s	Tx
-	Back to step 1	

Sample	m (g)	²¹⁰ Pb	²³⁴ Th1	²³⁴ Th2	²²⁶ Ra	Pb/Ra	Ra/U	²²⁸ Ra	²²⁸ Th	²²⁸ Ra/ ²²⁶ Ra	²²⁸ Th/ ²²⁸ Ra	U (ppm)	Th (ppm)
HAV1-P1-1	2.44	42.1 ± 5.1	36 ± 5	56.0 ± 4.0	41.7 ± 1.0	1.0	1.2	44.6 ± 2.2	43 ± 1	1.07 ± 0.06	0.97 ± 0.05	2.90 ± 0.40	10.59 ± 0.27
HAV1-P1-2	2.83	43.2 ± 2.8	42 ± 3	54.0 ± 2.0	42.7 ± 0.6	1.0	1.0	45.3 ± 1.2	46 ± 1	1.06 ± 0.03	1.02 ± 0.03	3.39 ± 0.24	11.35 ± 0.15
HAV1-P1-3	3.02	44.2 ± 5.0	51 ± 5	54.0 ± 3.0	41.4 ± 1.0	1.1	0.8	50.2 ± 2.1	48 ± 1	1.21 ± 0.06	0.95 ± 0.05	4.11 ± 0.40	11.77 ± 0.27
HAV1-P1-4	2.84	40.4 ± 5.1	41 ± 5	49.9 ± 3.4	40.8 ± 0.9	1.0	1.0	47.4 ± 1.9	52 ± 1	1.16 ± 0.05	1.11 ± 0.05	3.32 ± 0.40	12.87 ± 0.27
HAV1-P1-5	3.17	38.2 ± 4.7	41 ± 4	54.0 ± 3.0	42.1 ± 0.9	0.9	1.0	49.5 ± 2.0	49 ± 1	1.18 ± 0.05	1.00 ± 0.05	3.31 ± 0.32	12.14 ± 0.25
HAV1-P1-6	2.76	52.9 ± 5.2	48 ± 5	53.0 ± 3.0	42.3 ± 1.0	1.3	0.9	45.7 ± 2.1	48 ± 1	1.08 ± 0.06	1.04 ± 0.05	3.87 ± 0.40	11.67 ± 0.27
HAV1-P1-7	2.49	48.9 ± 3.0	50 ± 3	64.0 ± 2.0	43.9 ± 0.6	1.1	0.9	54.7 ± 1.4	54 ± 1	1.25 ± 0.04	0.98 ± 0.03	-	-
HAV1-P1-7	2.49	47.4 ± 3.8	54 ± 4	50.0 ± 2.0	41.3 ± 0.7	1.1	0.8	52.2 ± 1.3	54 ± 1	1.43 ± 0.04	1.03 ± 0.03	-	-
HAV1-P1-7	-	48.3 ± 2.4	51 ± 2	57.0 ± 1.4	42.8 ± 0.5	-	-	53.36 ± 1.0	54 ± 1	1.32 ± 0.03	1.00 ± 0.02	4.15 ± 0.19	13.19 ± 0.13
HAV1-P1-8	2.79	41.4 ± 6.0	48 ± 6	46.0 ± 4.0	40.1 ± 1.2	1.0	0.8	48.3 ± 2.5	50 ± 1	1.20 ± 0.07	1.03 ± 0.06	-	-
HAV1-P1-8	2.79	39.1 ± 3.9	37 ± 3	47.0 ± 3.0	38.1 ± 0.7	1.0	1.0	36.9 ± 1.3	41 ± 1	0.97 ± 0.04	1.12 ± 0.04	-	-
HAV1-P1-8	-	39.8 ± 3.3	39 ± 3	46.6 ± 2.4	38.6 ± 0.6	1.0	1.0	39.33 ± 1.2	44 ± 1	1.02 ± 0.03	1.08 ± 0.04	3.16 ± 0.22	10.70 ± 0.17
HAV1-P1-9	3.09	39.8 ± 2.8	41 ± 3	57.0 ± 2.0	39.6 ± 0.5	1.0	1.0	51.5 ± 1.2	49 ± 1	1.30 ± 0.03	0.96 ± 0.03	3.31 ± 0.24	12.11 ± 0.15
HAV1-P3-10	4.13	35.1 ± 3.5	33 ± 3	42.5 ± 2.3	32.8 ± 0.6	1.1	1.0	36.1 ± 1.2	35 ± 1	1.10 ± 0.04	0.98 ± 0.04	2.68 ± 0.27	8.65 ± 0.15
HAV2-P5-1	3.48	41.3 ± 3.8	42 ± 4	46.8 ± 2.6	34.8 ± 0.6	1.2	0.8	40.9 ± 1.1	41 ± 1	1.18 ± 0.04	1.01 ± 0.03	3.41 ± 0.31	10.15 ± 0.17
HAV2-P5-2	3.87	37.1 ± 3.4	38 ± 3	42.3 ± 2.4	38.3 ± 0.6	1.0	1.0	35.6 ± 1.2	36 ± 1	0.93 ± 0.03	1.01 ± 0.04	3.06 ± 0.27	8.85 ± 0.15
HAV2-P5-4	2.83	54.6 ± 4.9	46 ± 5	58.0 ± 3.0	43.1 ± 1.0	1.3	0.9	51.5 ± 2.2	49 ± 1	1.19 ± 0.06	0.94 ± 0.05	3.71 ± 0.40	11.94 ± 0.27
HAV2-P5-5	3.87	39.1 ± 2.0	41 ± 2	49.1 ± 1.4	38.4 ± 0.3	1.0	0.9	46.7 ± 0.6	47 ± 1	1.22 ± 0.02	1.00 ± 0.02	3.28 ± 0.17	11.45 ± 0.10
HAV2-P5-8	2.81	44.8 ± 4.9	41 ± 5	48.0 ± 3.0	33.3 ± 0.9	1.3	0.8	44.8 ± 2.0	43 ± 1	1.35 ± 0.07	0.96 ± 0.05	3.31 ± 0.40	10.59 ± 0.25
HAV2-P6-1	3.97	45.2 ± 3.8	42 ± 4	52.4 ± 2.5	38.6 ± 0.6	1.2	0.9	44.9 ± 1.2	47 ± 1	1.16 ± 0.04	1.04 ± 0.03	3.38 ± 0.31	11.45 ± 0.17
HAV2-P6-2	3.68	33.9 ± 3.7	40 ± 4	48.4 ± 2.5	40.6 ± 0.6	0.8	1.0	48.0 ± 1.2	47 ± 1	1.18 ± 0.03	0.97 ± 0.03	3.20 ± 0.30	11.47 ± 0.17

Supplementary table 1. Activity (Bq/kg) of main natural radionuclides of U and Th decay chains of the Havrincourt OSL sediment samples measured by gamma spectroscopy.

Sample	Sector	Profile	Unit	Preheat temperature (°C)	Recycling ratio	IR depletion ratio	Recuperation ratio (%)	Recovery test
HAV1-P1-1	HAV1	P1	4	260	1.00 ± 0.01	0.99 ± 0.01	1.1	0.98 ± 0.01
HAV1-P1-2	HAV1	P1	5a	260	1.00 ± 0.01	1.01 ± 0.01	1.2	1.01 ± 0.01
HAV1-P1-3	HAV1	P1	5a	260	1.00 ± 0.01	0.98 ± 0.01	1.0	1.00 ± 0.01
HAV1-P1-4	HAV1	P1	6b	260	0.99 ± 0.01	0.98 ± 0.01	0.9	0.98 ± 0.01
HAV1-P1-5	HAV1	P1	7	260	0.98 ± 0.01	1.00 ± 0.01	1.1	1.00 ± 0.01
HAV1-P1-6	HAV1	P1	7	260	0.98 ± 0.01	1.00 ± 0.01	1.0	0.98 ± 0.02
HAV1-P1-7	HAV1	P1	8	260	0.98 ± 0.01	0.99 ± 0.01	1.1	0.98 ± 0.01
HAV1-P1-8	HAV1	P1	8	260	0.98 ± 0.01	1.01 ± 0.01	1.0	0.96 ± 0.01
HAV1-P1-9	HAV1	P1	10	260	0.98 ± 0.01	1.00 ± 0.01	0.9	0.97 ± 0.01
HAV1 P3-10	HAV1	P3	4	270	1.01 ± 0.01	0.98 ± 0.01	1.9	1.02 ± 0.01
HAV2-P5-1	HAV2	P5	2	280	0.99 ± 0.01	1.00 ± 0.01	2.0	0.98 ± 0.01
HAV2 P5-2	HAV2	P5	4	270	0.99 ± 0.01	1.00 ± 0.01	1.2	1.01 ± 0.01
HAV2-P5-4	HAV2	P5	6a	260	1.01 ± 0.01	1.00 ± 0.01	1.5	0.99 ± 0.01
HAV2 P5-5	HAV2	P5	7	270	1.01 ± 0.01	1.00 ± 0.01	1.3	0.96 ± 0.01
HAV2-P5-8	HAV2	P5	8	260	0.98 ± 0.01	1.00 ± 0.00	1.0	0.98 ± 0.01
HAV2 P6-1	HAV2	P6	12	260	0.99 ± 0.01	0.99 ± 0.01	1.2	0.98 ± 0.01
HAV2 P6-2	HAV2	P6	12	250	1.00 ± 0.01	0.99 ± 0.01	1.3	0.96 ± 0.02

Table 2. SAR measurements results. Uncertainties on equivalent dose include a 1.2% error on the beta source calibration.

Havrincourt stratigraphical units	Time Range lower bound	Time Range upper bound
US2	29 330	16 669
US4	31 026	23 450
US5	31 536	28 304
<i>Hav2-N2 archaeological level</i>	<i>37 014</i>	<i>30 423</i>
US6	43 846	30 494
<i>US7 (rodents bones)</i>	<i>46 668</i>	<i>42 406</i>
US7	59 051	45 070
US8	66 082	50 511
US10	70 348	57 290
<i>Hav2-N1 archaeological level</i>	<i>74 026</i>	<i>61 422</i>
US12	103 720	61 070

Table S2. Time range endpoints for Havrincourt units (at level 95%). Results are represented in years before 2016 AD.

Sample	Sector	Profile	Unit	Depth (cm)	U (ppm)	Th (ppm)	K (%)	Water (%)	Alpha efficiency factor (a-value)
HAV1-P1-1	HAV1	P1	4	270	2.89 ± 0.40	10.62 ± 0.27	1.27 ± 0.05	35.0 ± 3.5	0.0446 ± 0.0023
HAV1-P1-2	HAV1	P1	5a	300	3.38 ± 0.24	11.39 ± 0.15	1.29 ± 0.02	43.9 ± 4.4	0.0413 ± 0.0035
HAV1-P1-3	HAV1	P1	5a	320	4.10 ± 0.40	11.81 ± 0.27	1.35 ± 0.04	42.2 ± 4.2	0.0443 ± 0.0027
HAV1-P1-4	HAV1	P1	6b	350	3.31 ± 0.40	12.92 ± 0.27	1.37 ± 0.05	39.3 ± 3.9	0.0405 ± 0.0021
HAV1-P1-5	HAV1	P1	7	370	3.30 ± 0.32	12.18 ± 0.25	1.34 ± 0.04	39.4 ± 3.9	0.0407 ± 0.0021
HAV1-P1-6	HAV1	P1	7	415	3.86 ± 0.40	11.71 ± 0.27	1.42 ± 0.05	38.4 ± 3.8	0.0414 ± 0.0020
HAV1-P1-7	HAV1	P1	8	450	4.14 ± 0.19	13.23 ± 0.13	1.65 ± 0.02	42.9 ± 4.3	0.0417 ± 0.0023
HAV1-P1-8	HAV1	P1	8	470	3.15 ± 0.22	10.73 ± 0.17	1.28 ± 0.03	38.2 ± 3.8	0.0394 ± 0.0019
HAV1-P1-9	HAV1	P1	10	500	3.30 ± 0.24	12.15 ± 0.15	1.52 ± 0.03	41.8 ± 4.2	0.0405 ± 0.0020
HAV1 P3-10	HAV1	P3	4	270	2.67 ± 0.27	8.68 ± 0.15	1.22 ± 0.01	36.1 ± 3.6	0.0453 ± 0.0024
HAV2-P5-1	HAV2	P5	2	170	3.40 ± 0.31	10.18 ± 0.17	1.41 ± 0.03	43.1 ± 4.3	0.0437 ± 0.0023
HAV2 P5-2	HAV2	P5	4	280	3.05 ± 0.27	8.87 ± 0.15	1.20 ± 0.03	39.0 ± 3.9	0.0424 ± 0.0022
HAV2-P5-4	HAV2	P5	6a	345	3.70 ± 0.40	11.98 ± 0.27	1.37 ± 0.04	43.8 ± 4.4	0.0416 ± 0.0025
HAV2 P5-5	HAV2	P5	7	410	3.27 ± 0.17	11.49 ± 0.10	1.37 ± 0.03	48.4 ± 4.8	0.0422 ± 0.0021
HAV2-P5-8	HAV2	P5	8	495	3.30 ± 0.40	10.62 ± 0.25	1.41 ± 0.04	38.5 ± 3.9	0.0401 ± 0.0019
HAV2 P6-1	HAV2	P6	12	530	3.37 ± 0.31	11.49 ± 0.17	1.58 ± 0.03	50.1 ± 5.0	0.0391 ± 0.0018
HAV2 P6-2	HAV2	P6	12	550	3.19 ± 0.30	11.51 ± 0.17	1.67 ± 0.03	49.5 ± 5.0	0.0406 ± 0.0021

Table 3. Havrincourt OSL samples. U, Th and K concentrations measured by gamma spectroscopy and parameters used for annual dose rate calculation (Sample depth from the surface; ratio of the water weight at saturation to dry sample weight; alpha efficiency determined using a ²⁴¹Am calibrated source).

Sample	Unit	Archaeological Level	Tissue	Initial thickness (μm)	Removed thickness dentine side (μm)	Removed thickness sediment side (μm)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{234}\text{U}$	$^{222}\text{Rn}/^{230}\text{Th}$	U (ppm)	Th (ppm)	K (%)
HAV1201	US6a	HAV2-N2	dentine enamel	1259 ± 157	147 ± 18	92 ± 12	1.130 ± 0.008 1.170 ± 0.008	0.097 ± 0.001 0.282 ± 0.001	0.52 1.00	4.10 ± 0.40	11.81 ± 0.27	1.35 ± 0.04
HAV1202	US12	HAV2-N1	dentine enamel	1527 ± 191	230 ± 29	166 ± 21	1.430 ± 0.007 1.449 ± 0.04	0.443 ± 0.004 0.355 ± 0.002	0.27 1.00	3.30 ± 0.40	10.62 ± 0.25	1.41 ± 0.04

Table 4. ESR/U-series parameters used for the Havrincourt horse teeth.

Site number	Lab number	Material	Unit	Archaeological Level	$^{13}\text{C}/^{12}\text{C}$ (‰)	^{14}C BP age (a)	^{14}C cal BP range (2σ) (a)
HAV F 1384GL	Oxford P-30581	Bone	6a	Hav2-N2	Failed due to low yield		
HAV2 F1384GL	Beta - 307416	Bone	6a	Hav2-N2	-21.4	27020 \pm 140	31264-31851
HAV F 1419A	Oxford P-30580	Bone	6a	Hav2-N2	Failed due to low yield		
HAV2 F1801A L19	Beta - 332604	Bone	6a	Hav2-N2	-20.9	28100 \pm 180	31414-32572
HAV F 2034A	Oxford P-30582	Bone	6a	Hav2-N2	Failed due to low yield		
HAV2 F840 H	Beta -328569	Marmot bones	7	--	-20.5	42090 \pm 380	44740-46154
HAV2 F941G1	Beta -328570	Ground squirrel bones	7	--	-20.8	40100 \pm 370	43058-44462

Table 5. C14 dates obtained on fossil bones from Havrincourt (calibrations according to Reimer et al. (2013), IntCal13)

Sample	Sector	Profile	Unit	Equivalent dose (Gy)	Annual dose rate (mGy/year)					Age (ka)
					alpha	beta	gamma	cosmic	total	
HAV1-P1-1	HAV1	P1	4	80.9 ± 1.5	0.50 ± 0.05	1.28 ± 0.08	0.87 ± 0.05	0.15 ± 0.02	2.80 ± 0.18	28.9 ± 1.9
HAV1-P1-2	HAV1	P1	5a	87.7 ± 1.6	0.48 ± 0.05	1.28 ± 0.08	0.89 ± 0.05	0.14 ± 0.01	2.79 ± 0.17	31.4 ± 2.0
HAV1-P1-3	HAV1	P1	5a	97.4 ± 1.8	0.59 ± 0.06	1.41 ± 0.09	0.98 ± 0.06	0.14 ± 0.01	3.12 ± 0.20	31.2 ± 2.1
HAV1-P1-4	HAV1	P1	6b	126.6 ± 2.2	0.52 ± 0.05	1.39 ± 0.09	0.98 ± 0.06	0.13 ± 0.01	3.01 ± 0.19	42.1 ± 2.8
HAV1-P1-5	HAV1	P1	7	150.1 ± 2.7	0.50 ± 0.05	1.35 ± 0.08	0.95 ± 0.05	0.13 ± 0.01	2.93 ± 0.17	51.2 ± 3.1
HAV1-P1-6	HAV1	P1	7	178.4 ± 3.2	0.55 ± 0.05	1.46 ± 0.09	1.00 ± 0.06	0.12 ± 0.01	3.13 ± 0.19	57.0 ± 3.6
HAV1-P1-7	HAV1	P1	8	165.0 ± 2.9	0.59 ± 0.05	1.60 ± 0.09	1.08 ± 0.06	0.12 ± 0.01	3.39 ± 0.19	48.7 ± 2.9
HAV1-P1-8	HAV1	P1	8	177.5 ± 3.2	0.45 ± 0.04	1.29 ± 0.07	0.88 ± 0.05	0.11 ± 0.01	2.73 ± 0.15	65.0 ± 3.8
HAV1-P1-9	HAV1	P1	10	202.1 ± 2.4	0.49 ± 0.04	1.43 ± 0.08	0.96 ± 0.05	0.11 ± 0.01	2.99 ± 0.17	67.6 ± 3.9
HAV1 P3-10	HAV1	P3	4	84.0 ± 1.8	0.44 ± 0.04	1.18 ± 0.06	0.77 ± 0.04	0.15 ± 0.02	2.53 ± 0.14	33.2 ± 2.0
HAV2-P5-1	HAV2	P5	2	81.3 ± 2.0	0.49 ± 0.05	1.33 ± 0.08	0.87 ± 0.05	0.17 ± 0.02	2.86 ± 0.17	28.4 ± 1.8
HAV2 P5-2	HAV2	P5	4	84.1 ± 1.8	0.44 ± 0.04	1.19 ± 0.07	0.78 ± 0.04	0.14 ± 0.01	2.55 ± 0.15	33.0 ± 2.1
HAV2-P5-4	HAV2	P5	6a	103.6 ± 2.0	0.52 ± 0.05	1.37 ± 0.09	0.95 ± 0.06	0.13 ± 0.01	2.97 ± 0.19	34.9 ± 2.3
HAV2 P5-5	HAV2	P5	7	140.5 ± 3.1	0.47 ± 0.04	1.27 ± 0.08	0.87 ± 0.05	0.12 ± 0.01	2.73 ± 0.16	51.5 ± 3.2
HAV2-P5-8	HAV2	P5	8	176.4 ± 3.2	0.47 ± 0.05	1.37 ± 0.08	0.91 ± 0.06	0.11 ± 0.01	2.86 ± 0.18	61.7 ± 4.0
HAV2 P6-1	HAV2	P6	12	209.3 ± 4.7	0.44 ± 0.04	1.38 ± 0.09	0.91 ± 0.06	0.11 ± 0.01	2.83 ± 0.18	73.9 ± 5.0
HAV2 P6-2	HAV2	P6	12	262.7 ± 6.9	0.44 ± 0.04	1.42 ± 0.09	0.91 ± 0.06	0.10 ± 0.01	2.87 ± 0.18	91.5 ± 6.2

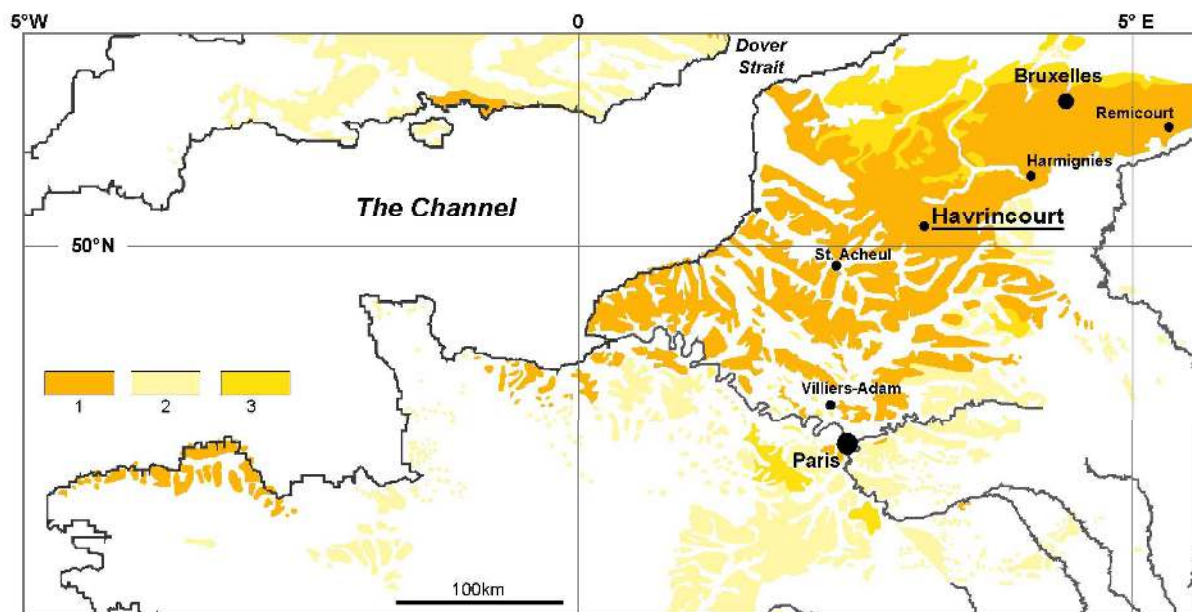
Table 6. Age results. Annual dose rates are calculated using table 3 data and most recent revised conversion factors (Guérin et al. 2011). Corrections due to moisture are calculated by applying a uniform factor, 0.8 ± 0.12 , to the water saturation level.

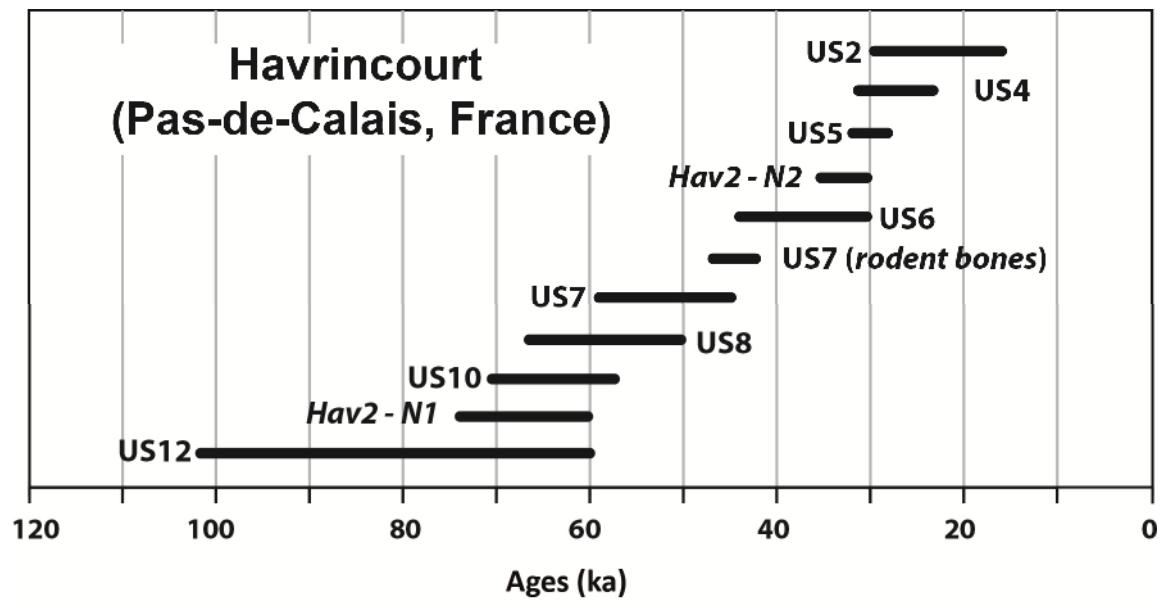
Samples	Unit	Archaeological Level	Tissue	U (ppm)	Equivalent dose D_E (Gy)	U uptake parameter p or n	$D_a \alpha$ Internal ^a ($\mu\text{Gy/a}$)	$D_a \beta$ ($\mu\text{Gy/a}$)	D_a ($\gamma + \text{cosm}$) ^b ($\mu\text{Gy/a}$)	D_a total ($\mu\text{Gy/a}$)	ESR/U-series ages (US or AU) ^c (ka)
HAV1201	6a	HAV2-N2	dentine	20.53 ± 0.13	43.15 ± 0.74	-0.9760 ± 0.1715	82 ± 50	147 ± 23	1040 ± 55	1269 ± 78	34.0 ± 2.0
			enamel	0.44 ± 0.01		-1.000 ± 0.0850					
HAV1202	12	HAV2-N1	dentine	17.15 ± 0.09	129.02 ± 2.75	-0.0042 ± 0.0008	745 ± 110	178 ± 17	1003 ± 50	1926 ± 122	67.0 ± 4.0
			enamel	3.95 ± 0.02		-0.6258 ± 0.0726					

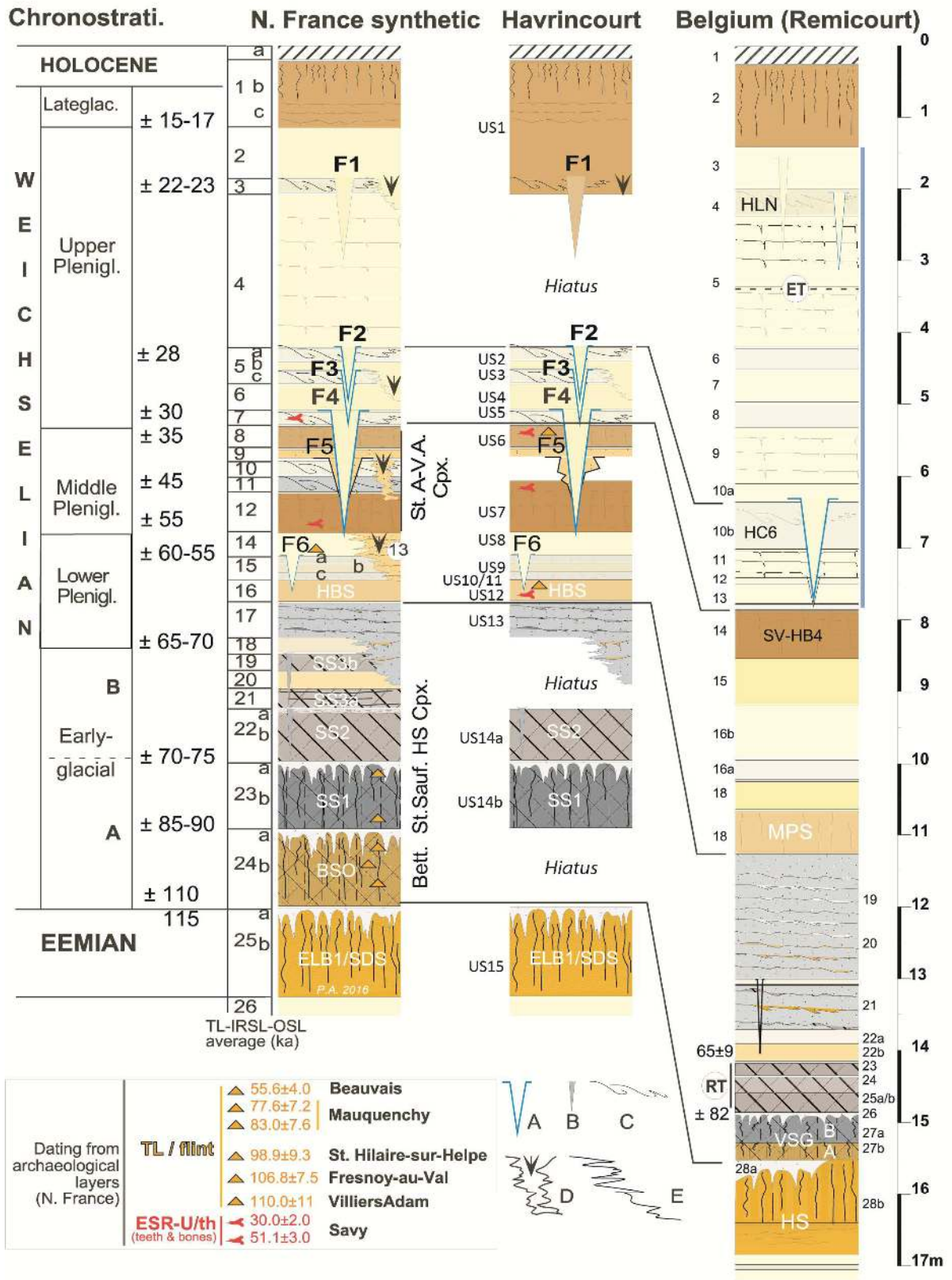
Table 7. ESR/U-series age results for the Havrincourt horse teeth. (a) A k-value of 0.13 ± 0.02 was used according to Grün & Katzenberger-Appel (1994); (b) Cosmic dose was estimated from the Prescott & Hutton's data (1994); (c) Uncertainties on the ESR/U-series ages (model US, Grün et al. 1988 or model AU, Shao et al. 2012) were calculated using Monte-Carlo approach (Shao et al., 2014).

Stratigraphical units	Time Range	
	lower bound	upper bound
US2	-29 361	-16 217
US4	-31 112	-23 442
US5	-31 548	-28 301
<i>Hav2-N2 archaeological level</i>	-36 887	-30 311
US6	-43 905	-30 528
<i>US7 (rodents bones)</i>	-46 712	-42 354
US7	-58 954	-45 005
US8	-66 263	-50 389
US10	-70 235	-57 620
<i>Hav2-N1 archaeological level</i>	-74 393	-60 937
US12	-101 611	-60 315

Table 8. Time range endpoints for Havrincourt units (at level 95%). Results are represented in years before 2016 AD.

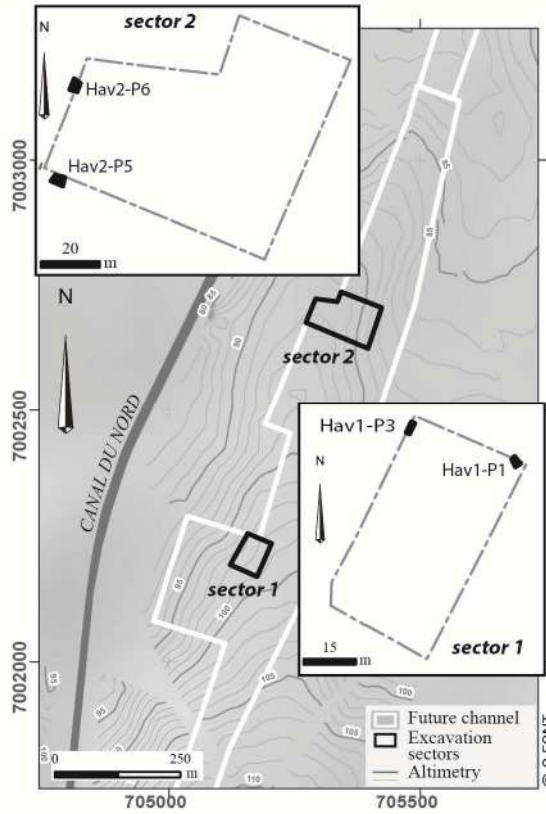








© D. GLIKSMAN



© E.GOVAL

Havrincourt (Pas-de-Calais, France)

