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Chronostratigraphy of two late Pleistocene loess-palaeosol sequences in the Rhône Valley (southeast France)

Mathieu Bosq^{1,*}, Sebastian Kreutzer^{2,3}, Pascal Bertran^{1,4}, Jean-Philippe Degeai⁵, Pauline Dugas^{1,6}, Annette Kadereit⁷, Philippe Lanos^{2,8}, Olivier Moine⁹, Nora Pfaffner¹⁰, Alain Queffelec¹, Daniela Sauer¹⁰

¹ PACEA, UMR 5199 CNRS - Université Bordeaux, Bâtiment B2, allée Geoffroy Saint Hilaire, 33615 Pessac, France

² IRAMAT-CRP2A, UMR 5060 CNRS - Université Bordeaux Montaigne, Maison de l'Archéologie, 33607 Pessac, France

³ Geography & Earth Sciences, Aberystwyth University, Aberystwyth, SY23 3DB, Wales, United Kingdom

⁴ Inrap, 140 avenue du Maréchal Leclerc, 33130 Bègles, France

⁵ ASM, UMR 5140 CNRS - Université de Montpellier III, route de Mende, 34199 Montpellier, France

⁶ Adera, PACEA-Transfert Sédimentologie & Matériaux. 162 avenue du Docteur Schweitzer 33600 Pessac

⁷ Heidelberg Luminescence Laboratory, Institute of Geography, University of Heidelberg, Germany

⁸ Géosciences Rennes – Université de Rennes I, 35042 Rennes, France

⁹ LGP, UMR 8591 CNRS - Université Paris I Panthéon-Sorbonne/Université Paris-Est-Créteil-Val-de-Marne (UPEC), place Aristide Briand, 92195 Meudon, France

¹⁰ Institute of Geography, University of Göttingen, Germany

*Corresponding author: Mathieu Bosq (mathieu.bosq@gmail.com)

ABSTRACT

A sedimentological and chronostratigraphical investigation was carried out on two loess sections located in the Mediterranean area in southeast France along the Rhône River (Lautagne) and the lower reach of a tributary of the Rhône River (Collias). High-resolution sampling (5 cm to 20 cm) for magnetic susceptibility, grain size distribution (including non-parametric end-member modelling), colour reflectance and geochemistry was performed. The chronology was based on luminescence dating of quartz grains and radiocarbon dating of small gastropod shells, coupled with hierarchical Bayesian modelling. The Collias section (~8 m thick) records the whole last climatic cycle. It comprises a thick red basal pedocomplex S1 developed during the Last Interglacial and the Early Glacial, similar to that observed elsewhere in southern and southeastern Europe. Loess deposition occurred during the Lower (L1L2) and the Upper Pleniglacial (L1L1). It was interrupted by soil

31 formation during the Middle Pleniglacial, of which a brown Bwk horizon has been preserved (L1S1).
32 By contrast, the ~5 m thick Lautagne section provides a detailed record of the Upper Pleniglacial.
33 Weakly developed hydromorphic soils are correlated with the Greenland Interstadials GI-4 to GI-2,
34 while the main period of coarse loess sedimentation corresponds to the Greenland Stadials GS-5 to
35 GS-2. At a regional scale, the time of loess deposition ranges between 38.5 ka and 12 ka, with a peak
36 at ~28–24 ka, overlapping with the maximal advance of the Alpine Ice Sheet (AIS). This strongly
37 suggests that regional glacier dynamics was the main driver of loess sedimentation.

38 *Keywords:* loess; southeast France; chronology; geochemistry; grain-size distribution; Last Glacial.

39 **1. Introduction**

40 Loess deposits are widespread across the European continent and constitute key terrestrial archives
41 for reconstructing the palaeoenvironments of the last climatic cycle. During the Last Glacial, drastic
42 reduction of the vegetation cover, increase in wind intensity and decrease in precipitation favoured
43 the global emission of dust (Hopcroft et al., 2015; Lunt and Valdes, 2002; Mahowald et al., 2006;
44 Schaffernicht et al., 2020). Loess accumulated at the periphery of the Eurasian Ice-Sheet (EIS) and
45 on the banks of major rivers draining mountain ice caps. Past advances of luminescence-dating
46 methods, such as optically simulated luminescence (OSL, Huntley et al., 1985) on quartz, and
47 infrared stimulated luminescence (IRSL, Hütt et al., 1988) or post-IR IRSL (pIRIR, Thomsen et al.,
48 2008) on feldspar and polymineral grains, have enabled the establishment of a robust chronological
49 framework of the phases of loess accumulation and soil formation (e.g., Frechen and Schirmer, 2011;
50 Fuchs et al., 2013; Guérin et al., 2017; Kreutzer et al., 2012; Lomax et al., 2014; Moska et al., 2019,
51 2015; Sauer et al., 2016; Thiel et al., 2011; Zens et al., 2018; Zöller et al., 2013). Simultaneous
52 improvements of radiocarbon dating by Accelerator Mass Spectrometry (AMS) made it possible to
53 analyse small charcoal pieces and carbonate biomineralisations (e.g., small terrestrial gastropod
54 shells, earthworm calcite granules) and also greatly contributed to support and refine previous loess

55 chronology in some regions (e.g., [Moine et al., 2017](#); [Újvári et al., 2016b](#)). Overall, the progress in
56 dating accuracy over the past decades highlighted the impact of millennial climate variations such as
57 Dansgaard-Oeschger (D-O) cycles upon loess sedimentation in Europe.

58 Yet, because of its patchy distribution and variable thickness, perimediterranean loess remains poorly
59 documented except for some publications ([Calvo et al., 2016](#); [Profe et al., 2016](#); [Wacha et al., 2018](#);
60 [Costantini et al., 2018](#)). Recent studies in the Po plain in Italy ([Cremaschi, 1990](#); [Cremaschi et al.,](#)
61 [2015](#); [Zerboni et al., 2015](#)) and Croatia ([Wacha et al., 2018](#)), as well as in the Ebro ([Boixadera et al.,](#)
62 [2015](#)) and Tagus basins ([Wolf et al., 2019, 2018](#)) in Spain suggested, however, that Pleistocene loess
63 covers considerable areas in perimediterranean regions. Last Glacial loess is also widespread in the
64 Rhône Valley, southeast France ([Bosq et al., 2018, 2020](#) and references therein). These deposits have
65 specific characteristics when compared to loess from the North-European Loess Belt (NELB),
66 including a coarser texture (main grain-size mode around 60 μm), polymodal grain-size distribution,
67 locally great thickness but discontinuous spatial distribution, high carbonate content and abundant
68 synsedimentary bioturbation. Such pattern is assumed to reflect the capture of particles in saltation
69 and short-term suspension by shrub vegetation close to the fluvial sources, in a milder climate than
70 that of the North European plains. Geochemical analyses show that loess deposits derived from the
71 rivers (Rhône, Rhine, Danube and Po) draining the Alpine Ice Sheet (AIS) have a similar, Ca-rich
72 composition (cf. [Bosq et al., 2020](#)). They are referred here as to “perialpine loess”.

73 This paper has the following objectives: (1) high-resolution multi-proxy analysis of two sections
74 (Collias and Lautagne) representative of the loess-palaeosol sequences of the Rhône Valley,
75 southeast France, (2) development of an accurate chronological framework using a hierarchical
76 Bayesian model based on OSL and AMS ^{14}C ages of the section of Lautagne, and (3) comparison of
77 the chronology of loess deposition with AIS fluctuations and the North Greenland Ice Core Project
78 (NGRIP) ice record.

80 2. Materials and methods

81 2.1. Study sites, description and sampling

82 The sequence Collias (43.953°N; 4.466°E; 100 m a.s.l.) is located on the left bank of the Gardon
83 River, upstream of its confluence with the Rhône (**Fig. 1A, 1B**). In this area, loess deposits reaching
84 locally 10 m thickness were recognised in the 1950s and 1960s ([Bonifay, 1962](#); [Mazenot, 1956](#);
85 [Tricart, 1952](#)). Loess overlies Lower Miocene molasse (noted m1v on the 1:50,000 geological map,
86 <http://infoterre.brgm.fr/>) and extends from the foot of a Lower Cretaceous (n4-5U) limestone massif
87 to the alluvial plain of the Alzon river (**Fig. 1C**). A previous study has demonstrated that the
88 geochemical composition of alluvium from the Gardon River (as well as all the rivers from the
89 French Massif Central) differs from that of loess of the Rhône Valley, including the Collias samples
90 ([Bosq et al., 2020](#)). The geochemical data also revealed that the dust was mainly supplied by the bed
91 of the Rhône River (at that time a braided river, carrying the sediment loaded meltwater of the
92 Alpine (and Jura) glaciers). [Bonifay \(1962\)](#) distinguished two loess generations and assigned them to
93 the Last Glacial ("Series I") and the Penultimate Glacial ("Series II"). According to the same author,
94 the two generations are separated by an erosional discontinuity attributed to the Last Interglacial. The
95 studied section is a sub-vertical outcrop created during the construction of a forest road. A
96 Mediterranean climate with low rainfall (Mean Annual Precipitation, MAP = 763 mm), hot summers
97 ($T_{\max} \geq 22^{\circ}\text{C}$) and relatively high annual temperatures (Mean Annual Temperature, MAT = 15.2 °C)
98 characterises the area (meteorological data for the period 1981–2010;
99 <https://donneespubliques.meteofrance.fr/>).

100 The sequence Lautagne (44.904°N; 4.897°E; 177 m a.s.l.) is located south of Valence on the left
101 bank of the Rhône (**Fig. 1D**), on a river terrace (Fw) attributed to the Middle Pleistocene ([Mandier,](#)
102 [1988](#)), showing a well-developed rubified palaeosol. Two test pits were dug during archaeological

excavations led by the *Institut national de recherches archéologiques préventives* (Inrap) (see **Fig. A1** in **Appendix A**). The fluvial gravel is buried by loess, reaching a thickness of up to 5 m (profile A) and gradually decreasing towards the edges of the plateau (profile B). Lautagne is located at the transition between a semi-continental climate to the north and a Mediterranean climate to the south, with a MAP = 923 mm and a MAT = 13.3 °C.

Excavation and manual cleaning of the sections created successive vertical panels (1 m to 2 m high and > 1 m wide) separated by steps, making description and sampling easier. The lithofacies codes were taken from Miall (1996), and the soil horizons were classified according to the FAO Guidelines for Soil Description (FAO, 2006) and the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). Samples were collected for magnetic susceptibility, grain-size distribution and colourimetry at 5 cm depth-resolution, and for geochemistry at 20 cm depth-resolution. In total, 164 (Collias) and 98 (Lautagne) samples were collected and analysed (**Figs. 2** and **3**). In addition, eight blocks of sediment (15 cm x 10 cm x 7 cm) were extracted from each section for thin section preparation according to the method described by Guilloché (1980). The micromorphological description of the samples was carried out according to the recommendations of Stoops (2003).

2.2. Bulk magnetic susceptibility

Measurements of the specific-mass magnetic susceptibility (χ) of each sample were performed in the laboratory using a Bartington MS2B at room temperature. The results are expressed in $10^{-6} \text{ m}^3/\text{kg}$. The dry, bulk sedimentary material was homogenised and compressed in a 10 ml plastic cylinder. χ values reflect the concentration of minerals with ferrimagnetic properties (mainly magnetite and maghemite). Nevertheless, this proxy can be biased by the grain-size distribution of magnetic grains. Indeed, ferrimagnetic grains of the superparamagnetic grain-size (SP, $<0.03 \text{ }\mu\text{m}$) have a significantly higher χ than single-domain (SD, $>0.03 \text{ }\mu\text{m}$) or multi-domain (MD, $>\sim 10 \text{ }\mu\text{m}$) particles (Thompson and Oldfield, 1986). The use of the frequency dependent magnetic susceptibility (χ_{FD}) partially

127 resolves these limitations (Obrecht et al., 2019). This parameter is the relative difference between the
128 mass magnetic susceptibility values measured at low frequency (0.46 kHz) and high frequency (4.65
129 kHz) (χ_{LF} and χ_{HF} respectively). χ_{FD} (expressed in %) was calculated as follows:

130
$$\chi_{FD} = \frac{(\chi_{LF} - \chi_{HF})}{\chi_{LF}} \times 100$$

131 χ_{FD} is a measure of the relative contribution of SP ferrimagnetic particles approaching the SP-SD
132 threshold that are formed exclusively *in-situ* (e.g., Dearing et al., 1996; Maher and Taylor, 1988).
133 Therefore, χ_{FD} is considered to be a very efficient proxy for determining the weathering intensity
134 (Buggle et al., 2014; Dearing et al., 1996).

135 **2.3. Grain-size distribution and end-member modelling**

136 The samples for grain-size distribution analysis were processed using a Horiba LA-950 laser particle
137 size analyser. After passing the samples through a 2 mm sieve to remove the coarser fraction
138 (secondary carbonate concretions, shells, gravels and roots), the sample pre-treatment included
139 suspension in sodium hexametaphosphate (5 g/l) and hydrogen peroxide (35%) at room temperature
140 for 12 h. As recommended by Schulte et al. (2016), the carbonates were not removed. Then, the
141 suspension was subjected to 60 s ultrasonification to achieve optimal dispersion. The Mie solution to
142 Maxwell's equation provided the basis for calculating the particle size distribution (ISO, 2009; Jones,
143 2003), using a refractive index of 1.333 for water and 1.55i – 0.01i for the particles (see Appendix of
144 Sitzia et al., 2017 for details on the procedure). The upper limit of clay measured by laser
145 granulometry was set at 8 µm after calibration by the sieve-pipette method as described in Bosq et al.
146 (2018). Finally, the *Grain Size Index* (GSI) defined by Antoine et al., 2009a was calculated. The GSI
147 is the ratio between coarse silt (52–26 µm) and fine silt plus clay (< 26 µm).

148 Grain-size distribution can provide key information on the provenance, mechanisms and/or distance
149 of transport, and the depositional environment of sediments (e.g., Bagnold and Barndorff-Nielsen,

150 1980; Újvári et al., 2016a; Vandenberghe, 2013). Two approaches have been developed to
151 decompose grain-size distributions and to quantify dominant subpopulations in aeolian sediments: (i)
152 parametric curve fitting using a mixture of log-normal (Bosq et al., 2018; Qin et al., 2005) or Weibull
153 distribution functions (Sun et al., 2002) and (ii) non-parametric end-member modelling analysis
154 (EMMA) (Dietze et al., 2012; Vriend and Prins, 2005; Weltje, 1997; Weltje and Prins, 2007; Dietze
155 and Dietze, 2019). In this study, the EMMA approach was applied using the MATLAB® GUI
156 software of AnalySize developed by Paterson and Heslop (2015). The main advantage of this method
157 is that it describes an entire grain-size dataset as a mixture of distinct unimodal or polymodal
158 subpopulations (Dietze et al., 2012; Weltje, 1997; Weltje and Prins, 2007). The analysis was
159 arbitrarily restricted to the grain-size class [$>1\ \mu\text{m}$ to $<678\ \mu\text{m}$] to eliminate a large number of zeros
160 that cause numerical instabilities in the treatment. The determination coefficient R^2 was calculated to
161 identify the minimum number of end-members (EMs) (q) necessary for correct statistical
162 interpretation. Following this principle of parsimony, an EM model with $q=3$ was chosen as a
163 significant improvement of R^2 was obtained by going from 2 to 3 EMs while the improvement was
164 reduced from 3 to 4 EMs (see Fig. A2). This model explains 97.8% of the total variance of the full
165 grain-size dataset. Then, the distribution of each EM was split into different populations by the
166 parametric curve fitting method using the R (R Core Team, 2019) package ‘mixdist’ (Macdonald and
167 Du, 2015) to identify the different modes. A log-normal distribution was used.

168 2.4. Spectrocolourimetry

169 The colour of moist sediments was determined in the field using the Munsell soil colour chart
170 (Munsell, 2000). The colour of the dry, crushed and homogenised samples was then measured in the
171 laboratory using an Avantes AvaSepc-2048 fibre-optic spectrometer. The instrument was equipped
172 with an optic fibre probe (1 mm diameter) that was placed at a short distance (2 mm) from the
173 smooth surface of the sample. An AvaLight-Hal was used as the light source, and the equipment was
174 calibrated with a white reference sample (Halon D65). Three measurements per sample were

performed, and the average was then calculated. The spectral information obtained was converted into the CIELAB (L^* , a^* , b^*) system (CIE, 1976) using Avasoft 7.5 software. The variable L^* indicates the lightness on a scale from 0 (black) to 100 (white) while the variables a^* and b^* express the colour in chromatic coordinates on the red-green (positive a^* - negative a^*) and blue-yellow (positive b^* - negative b^*) scales.

Colour differences between yellowish loess and reddish-brown palaeosols are mainly a consequence of goethite and hematite concentrations (Ji et al., 2001). The chromaticity values a^* is closely related to the relative abundance of pedogenic hematite (e.g., Lukić et al., 2014).

2.5. Geochemical analysis

The sediment was passed through a 100 μm sieve to remove coarse sand grains, ferruginous nodules, carbonate concretions and other debris such as calcified roots, mollusc shells and earthworm calcite granules, which may disturb the results of the geochemical analysis. The fine fraction $<100 \mu\text{m}$ was ground and pressed into pellets for X-ray fluorescence (ED-XRF) using a portable Bruker Tracer 5i. Two measurements were taken under vacuum on all samples, one at 15 kV and 100 μA for 300 s without a filter to quantify light elements (Na, Mg, Al, Si, P, K, Ti, V, Cr, Mn, Fe) and the other at 50 kV and 35 μA for 120 s with the Cu75, Ti25, Al200 filter for heavy elements (Ni, Zn, Ga, As, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Nd, Hf, Pb, Th) and Ca. The instrument was calibrated by use of the CloudCal v3.0 application (Drake, 2018; <https://github.com/leedrake5/CloudCal>), using the algorithm proposed by Lucas-Tooth and Price (1961). The calibration was performed using the geochemical composition of 43 loess and alluvial samples determined by Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) and ICP-Mass Spectrometry (ICP-MS) at the Service d'Analyse des Roches et des Minéraux (CRPG-SARM, Nancy, France) according to a previously published methodology (Bosq et al., 2020). Only the elements for which the

determination coefficient R^2 between the analytical results of the ED-XRF and the ICP-AES/ICP-MS was greater than 0.7 were considered (cf. **Figs. A3 and A4**).

A wide variety of geochemical indices based on major and trace elements has been developed to study dust provenance, grain-size sorting and weathering intensity in European loess (cf. [Bosq et al., 2020](#)). For the purposes of this study, we focused on the following element ratios and indices: Ti/Al, Si/Al, CPA, Rb/K, Fe/Al, and Ca/Al. Al is considered here as the invariant element. Ti, mainly in the form of oxides (anatase, brookite, rutile), forms inclusions in mafic minerals, especially biotite, which is concentrated in the fine fraction ([Young and Nesbitt, 1998](#)). The Ti/Al ratio is used here as an indicator of the homogeneity of the sedimentary source ([Sheldon and Tabor, 2009](#)). The Si/Al ratio is sensitive to grain-size sorting since Si-rich tectosilicates (quartz, feldspars) are over-represented in the coarser fractions, whereas Al-rich phyllosilicates constitute a large part of the finer fractions ([Bouchez et al., 2012](#); [Guo et al., 2018](#); [Liang et al., 2013](#)). Weathering indices are based on the selective removal of soluble and mobile elements (particularly alkali and alkaline earth elements) during pedogenesis ([Buggle et al., 2011](#); [Nesbitt and Young, 1982](#)). The weathering intensity of silicates was quantified using the *Chemical Proxy of Alteration* (CPA) (in molar proportion):

$$CPA = 100 \times \frac{Al_2O_3}{(Al_2O_3 + Na_2O)}$$

CPA (originally called Chemical Index of Weathering (CIW') by [Cullers, 2000](#)) was considered a proxy for plagioclase weathering intensity by [Buggle et al. \(2011\)](#). The CPA is particularly adapted to poorly weathered sediments since weathering first impacts plagioclases rather than K-feldspars ([Nesbitt and Young, 1989](#)). Besides the CPA, the K/Rb ratio was used to estimate the weathering intensity of K-bearing minerals ([Nesbitt et al., 1980](#); [Wronkiewicz and Condie, 1990](#)), since K is more mobile than Rb due to its smaller ionic radius. Rb is hosted by K-feldspars, micas and clay minerals ([Heier and Billings, 1970](#); [Nesbitt et al., 1980](#)). As Ca is essentially hosted by calcite, the Ca/Al ratio allows to evaluate the depth distribution of calcite along the sequence, in particular the

secondary precipitation of calcite of pedogenic origin at certain profile depths, provided that the contents of plagioclases and primary calcium carbonate are roughly constant across the profile. The Fe/Al ratio is used to distinguish the B horizons of soils that are relatively enriched in Fe, due to the formation of immobile iron oxides such as magnetite (Fe_3O_4), hematite (Fe_2O_3) and goethite ($\text{FeO}(\text{OH})$) (Reimann et al., 2014).

2.6. Chronological data

2.6.1. Luminescence dating

The two sites Lautagne and Collias were subjected to luminescence dating at the IRAMAT-CRP2A (Université de Bordeaux-Montaigne) between 2016 and 2019. In both cases, the samples were extracted under daylight using steel cylinders. In total, we prepared 18 samples (10 from Lautagne, including 8 from section A and 2 from section B, and 8 samples from Collias) to extract the fine-grain (4–11 μm) (Lautagne) and coarse-grain (90–200 μm) (Collias) quartz fractions (see **Table 1**). Additionally, we extracted coarse-grain quartz separates for Lautagne and the K-feldspar fraction of 2 samples from Collias for cross-checks. The sample preparation was supported by the luminescence laboratories of the Justus-Liebig University Giessen (Germany) and the University of Bayreuth (Germany), following routine luminescence dating preparation methods (Preusser et al., 2008). The quartz samples were subjected to OSL measurements, applying the single-aliquot regenerative (SAR) dose protocol (Murray and Wintle, 2000). Equivalent doses (D_e) were measured on Freiberg Instruments *lexsyg research* luminescence readers (Richter et al., 2013), and the data analysis was performed with the R (R Core Team, 2019) package ‘Luminescence’ (Kreutzer et al., 2012b, 2020). We applied the average dose model (G. Guérin et al., 2017) to samples from Lautagne and the ‘baSAR’ approach (Combès et al., 2015; Mercier et al., 2016) to samples from Collias to calculate the average dose and the central dose respectively, and their corresponding standard errors. Dose-rate measurements relied on *in situ* gamma-dose rate measurements at Lautagne (cf. Løvborg and Kirkegaard, 1974; Mercier and Falguères, 2007) and high-resolution gamma-ray spectrometry

(procedure at the IRAMAT-CRP2A, cf. [Guibert and Schvoerer, 1991](#)). In addition, we measured U, Th, K concentrations for all samples from both sites. The online calculator *DRAC* ([Durcan et al., 2015](#)) in version 1.2 provided the final luminescence ages. We show full details of the luminescence dating, including further references, in **Appendix B**.

2.6.2. *AMS radiocarbon dating*

Last Glacial loess-palaeosol sequences (LPS) in southeast France lack organic remains that can be easily dated by the radiocarbon method. To overcome this problem, recent studies have been undertaken, which have shown that calcitic biomineralisations such as terrestrial gastropod shells or earthworm granules can be used to obtain a precise chronology (e.g., [Moine et al., 2017](#); [Újvári et al., 2016b](#)). The advantage of this approach is that these carbonates are relatively abundant in loess. In the past, mollusc shells have often been avoided for dating because large taxa incorporate carbon from the substrate, which causes apparent radiocarbon-age increases up to several thousand years ([Evin et al., 1980](#); [Goodfriend and Stipp, 1983](#)). However, several studies have shown that this effect is much more limited and generally negligible for small (<10 mm) gastropods ([Brennan and Quade, 1997](#); [Pigati et al., 2010](#)).

Ten litres of bulk sediment have been wet sieved on a 425- μ m mesh. Then, gastropod shells and earthworm calcite granules were cleaned by ultrasonic treatment and were analysed in the following laboratories: (i) the AMS facilities of the Hertelendi Laboratory of Environmental Studies, Institute for Nuclear Research at Debrecen (Hungary) ([Molnár et al., 2013](#)); (ii) the Radiocarbon dating centre at Lyon (France) within the framework of the ARTEMIS programme and (iii) the Centre for Isotope Research at Groningen (Netherlands) ([Dee et al., 2020](#)). Conventional radiocarbon ages were calibrated to calendar ages with the *IntCal13* calibration curve ([Reimer et al., 2013](#)), using the software *Calib* in version 7.0.4 ([Stuiver and Reimer, 1993](#)). Calibrated ages are reported as age ranges at the 2 sigma (σ) confidence level (95.4%).

2.6.3. Bayesian age modelling

In order to obtain a robust chronology of the best-dated sequence (Lautagne A), a Bayesian age model was built using the software *ChronoModel* (version 2.0.18) (Lanos and Dufresne, 2019; Lanos and Philippe, 2017, 2015). This software allows the calculation of *a posteriori* ages by considering the stratigraphic constraints between the samples. After removal of outliers, an age model was built for the period 35–15 ka cal. b2k (before the year 2000). We used the default configuration of Monte-Carlo Markov Chain (MCMC) parameters proposed by the software (3 chains, 1,000 burn iterations, and 500 batch iterations with a maximum of 20 batches, and 100,000 acquisition iterations with a thinning interval of 10). This approach may result in slightly underestimated age uncertainties because *ChronoModel* does not yet allow to specify shared systematic uncertainties. However, given the large uncertainties of the OSL ages, this potential problem does not affect the overall interpretation of our results.

In total, 15 ^{14}C and OSL dates were used for establishing the chronology of the section Lautagne A (see **Fig. A5**). The highest posterior density (HPD, 95%) of the ^{14}C and OSL ages was calculated according to the method detailed by Banks et al. (2019). The posterior age probability distributions for each sample are compiled in **Tables 1** and **2**.

3. Results

3.1. Lithofacies and soil horizons

Homogeneous loess (Fm)

This lithofacies consists of massive, homogeneous calcareous yellowish brown (10YR 5/4 to 2.5Y 6/4) coarse silt and fine sand (**Fig. 4A**). Bioturbation features (root channels, burrows) and secondary carbonate concretions (rhizoconcretions, pseudomycelium) are abundant (**Figs. 4, 5E, 5F, 6E** and

294 **6F)**. At Lautagne, a platy microstructure due to former segregation ice lenses (e.g., [Van Vliet-Lanoë,](#)
295 [1985](#)) is visible between 1.9 m and 3.2 m depth (**Fig. 6G**).

296 This lithofacies is dominant in both sections and interpreted as being of aeolian origin. Due to
297 abundant secondary calcium carbonate, these loess units are designated as Ck or BCk horizons
298 according to [FAO \(2006\)](#).

299 *Bedded calcareous sandy loess (Fh)*

300 This facies consists of regularly alternating sandy and light yellowish-brown silty (2.5Y 6/4) beds
301 with lenses of small subangular limestone fragments (**Fig. 5B**). The lenses are ca 1 cm thick and
302 generally up to 1 m wide (**Fig. 4B**). This lithofacies is interpreted as loess mixed with local coarser
303 material, redistributed by overland flow.

304 *Massive loess colluvium (Dmm)*

305 Massive brown coarse silty deposits, containing scattered gravels, and characterised by poor sorting,
306 greater porosity and few charcoal fragments, are interpreted as colluviated loess (**Figs. 2, 4B** and
307 **5A**).

308 *Ploughed topsoil horizon (Ap)*

309 The topsoil horizon at Lautagne contains bricks, pottery and charcoal fragments and results from the
310 reworking of loess caused by agricultural practices during the Holocene.

311 *Buried topsoil horizons with redox features (Ag)*

312 Five units in the section Lautagne A consist of thin (10–20 cm), slightly bleached (2.5Y 6/4 to 2.5Y
313 5/6), calcareous silt with scattered small Fe-Mn nodules. Their boundaries are sharp and show
314 deformations due to stretching downslope (**Fig. 4E**). These horizons are characterised by (i)
315 bleaching resulting from hydromorphic processes (iron reduction and removal from the horizon); (ii)

316 a slightly finer texture compared to the underlying loess; (iii) weak staining by organic matter and
317 (iv) abundant carbonate concretions.

318 These units, which often overlie BC horizons, are interpreted as topsoil Ag horizons, indicating
319 seasonal waterlogging (FAO, 2006) that have been deformed by slope dynamics after burial,
320 probably in a periglacial context, possibly by solifluction.

321 Brown Bwk and BC horizons

322 These horizons are characterised by moderate weathering as indicated by (i) a higher proportion of
323 clay; (ii) a brown colour (10YR 5/6 to 10YR 6/6) related to the formation of iron oxides; (iii) partial
324 dissolution of carbonates associated with carbonate precipitation in the underlying horizon. The Bwk
325 horizon underwent strong secondary accumulation of calcite forming large rhizoliths, which justifies
326 the addition of the suffix -k. Poorly developed (incipient) horizons showing a range of features
327 otherwise typical of Bw horizons are here referred to as BC horizons.

328 Rubified Bw and Bwk horizons

329 Yellowish red (5YR 4/6) to reddish brown (7.5YR 4/6), compact calcareous clayey silt units,
330 exhibiting a massive or prismatic to blocky structure, are interpreted as rubified Bw horizons.
331 Bioturbation (by burrows and roots) is abundant, and black Fe-Mn hypocoatings cover many ped
332 faces (**Fig. 6D**). There is no microscopic evidence of clay illuviation (e.g., clay coatings, clay
333 papules) (**Fig. 5C**). Decalcification of the groundmass is complete, while some channels are filled by
334 slightly calcareous loessic sediment. Secondary carbonate impregnations are also visible.

335 Calcrete (Ckm horizon)

336 At Collias, the redistribution of CaCO₃ led to the formation of an indurated laminar crust and vertical
337 rhizoconcretions more than 10 cm long at the bottom of the profile, designated as Ckm horizon (**Fig.**
338 **4A, 4C**).

339 **3.2. Stratigraphy**

340 The section Collias comprises five main stratigraphic units, from bottom to top (**Figs. 2 and 4**):

- 341 - Calcrete (Ckm horizon) overlain by rubified Bw and Bwk horizons, forming a pedocomplex
342 referred to as S1;
- 343 - Bedded calcareous sandy loess (L1L2), 2.5 m thick, with bioturbation and diffuse lower
344 boundary;
- 345 - Brown Bwk horizon (L1S1), 0.5-0.6 m thick, whose upper boundary is an erosional surface;
- 346 - Colluvium (0.2 m) overlain by 2.8 m thick primary loess (L1L1);
- 347 - Holocene brown Cambisol (S0), about 1 m thick, predominantly composed of material that
348 has been reworked and translocated in the course of agricultural land use and terracing of the
349 above land (presently used as olive plantation).

350 The loess sequence at Lautagne (**Fig. 3**) covers Pleistocene gravels that were reached locally at a
351 depth of 5.3 m during the archaeological excavation. Three main units (I-III) were distinguished:

- 352 - Reddish colluviated loess, up to 0.5 m thick (L1S1);
- 353 - Sandy, calcareous loess, 4.7 m thick (L1L1), including three incipient palaeosols (P3, P2 and
354 P1), each consisting of an Ag-BC profile;
- 355 - Holocene Luvisol (S0), locally preserved from erosion due to agriculture within Gallo-
356 Roman pits, and with a ploughed topsoil (Ap horizon).

357

358 **3.3. Analytical data: magnetic susceptibility, colourimetry, grain-size and geochemistry**

359 An overview of the main physical and chemical properties of the two sequences is provided in
360 **Figures 2 and 3.**

361 Both sections are characterised by large GSI fluctuations with maximum values in the bedded loess
362 at Collias (between 4.15 m and 4.50 m depth) and in the homogeneous (primary) loess at Lautagne A

363 (at 3.15-3.30 m depth). The proportion of the coarse fraction ($>100\ \mu\text{m}$) ranges from 6.3% to 34.8%
364 at Collias and reflects slope inputs mixed with aeolian dust and/or pedogenic carbonate concretions.

365 The variations in low-frequency magnetic susceptibility (χ_{LF}) coincide with lithofacies changes in
366 both sequences. The highest values ($\chi_{\text{LF}} \geq 0.4 \cdot 10^{-6}\ \text{m}^3/\text{kg}$) are found in palaeosol horizons while the
367 lowest values are typical of primary loess (L1L1) and bedded loess (L1L2), except for the Bwk
368 horizon L1S1 at Collias that has relatively low χ_{LF} values (between 0.25 and $0.39 \times 10^{-6}\ \text{m}^3/\text{kg}$).
369 L1S1 has also χ_{FD} values above 10%, indicating *in situ* neoformation of superparamagnetic (<0.03
370 μm) pedogenic particles. The lack of correlation between χ_{LF} and χ_{FD} values suggests that larger
371 ferrimagnetic minerals (MD and SD) have little or no contribution to increased magnetic
372 susceptibility.

373 A correlation exists between magnetic susceptibility and other proxies such as clay content and
374 chromaticity a^* . The highest values of chromaticity a^* range between 5.6 and 13.5 and are associated
375 with clay contents higher than 25%, especially in the pedocomplex S1 at Collias. At Lautagne A, the
376 BC horizons are characterised by relatively high a^* values (≥ 4), and an increase in clay content. In
377 contrast, a^* values and clay contents decrease in homogeneous loess (on average 8-14% clay at
378 Lautagne A and 9-19% clay at Collias).

379 In both sequences, the element ratio Ti/Al is almost constant, with values between 0.07 and 0.09,
380 indicating stable and homogeneous sediment sources. The Si/Al ratio covariates with CSI and
381 increases significantly in loess while it decreases in palaeosol horizons, which reflects enrichment in
382 aluminosilicates (clay minerals) in the latter. Plagioclase and K-feldspar weathering, represented by
383 CPA and Rb/K, respectively, is more intense in B and BC horizons than in underlying loess. The
384 weathering indices record maximum values in S1 with a CPA of about 96 and a Rb/K ratio of 63. Ag
385 horizons exhibit higher concentrations of K-bearing minerals than BC horizons, which is related to
386 the presence of illite in the fine fraction.

3.4. Variation in Grain-size distribution and end-member modelling

The grain-size distribution of all samples is polymodal, with the main mode around 60–70 μm (**Figs. 7A, 7B**). The EM modelling algorithm is able to distinguish three components (EM-1, EM-2 and EM-3) that explain well the observed variability in grain-size distribution ($R^2 > 0.9$ for 95% of the samples analysed, i.e. 248 out of a total of 261).

EM-1 is characterised by a unimodal distribution with the main mode at 68 μm (Fig. 7C). This subpopulation explains 49.2% of the variance at Lautagne and 19.3% at Collias respectively. EM1 is interpreted as coarse particles that were transported by wind, through saltation and short-term suspension at very low altitude during storm events (Tsoar and Pye, 1987; Vandenberghe, 2013).

EM-2 has a roughly bimodal distribution with one mode in the medium silt fraction (45 μm) and another in fine silt (16 μm). It represents 40.3% of the variance at Collias and 33.0% at Lautagne A. The coarse mode (45 μm), common in loess deposits, involves short-term transport over greater distances than EM-1 (Li et al., 2018; Muhs and Bettis III, 2003; Pye, 1995). Recent observations in China showed that dust of the same grain-size mode (~ 40 μm) is collected 10 m above the ground during spring and early summer (Sun et al., 2003). The finest mode (16 μm) corresponds to dust transported through long-term suspension in the atmosphere at high altitude (tens to hundreds of metres above the ground (Sun et al., 2003). Observations in the Cél oasis (China) showed that these two components (45 μm and 16 μm) could derive from a single local source (Lin et al., 2016).

EM-3 is poorly sorted and has a polymodal distribution with the main mode of 183 μm and three minor modes (82 μm , 15 μm and 3 μm) (**Fig. 7C**). EM-3 explains 40.4% of the variance at Collias and 17.8% at Lautagne A. The presence of medium to coarse sand and poor sorting indicate mixing of materials from different sources (in surface horizons especially by agricultural practices) and the addition of autochthonous materials into the aeolian sediments by slope processes. EM-3 has probably a polygenic origin (aeolian and colluvial).

411 Fine grains ($\sim 3.0 \mu\text{m}$ mode) are represented by a tail in the grain-size distribution curves of all three
412 subpopulations (**Fig. 7C**). This tail is sometimes considered as an artefact (Nottebaum et al., 2015),
413 and is reported in most European and Asian loess deposits (Vandenberghe, 2013). The fine particles
414 could indicate long-term suspension transport in the atmosphere (“continuous background dust”)
415 (Sun et al., 2002). Alternative hypotheses include: (i) fine particles transported by wind as aggregates
416 (Újvári et al., 2016a); (ii) clay adhesion on coarser grains (Qiang et al., 2010) or (iii) pedogenic
417 processes (Bronger and Heineke, 1990; Sun et al., 2000).

418 Both sequences show the same overall pattern of EM distribution (**Fig. 8**), i.e. glacial loess deposits
419 are dominated by the coarse component (mainly EM-1), whereas interglacial and interstadial
420 palaeosol horizons are dominated by the fine component (EM-2). Topsoils and bedded loess that
421 have undergone reworking are characterised by a higher EM-3 score.

422 **3.5. Chronological data**

423 **3.5.1. Luminescence ages**

424 **Table 1** lists the luminescence ages in the two sections. Additional information is provided in
425 **Appendix B**.

426 **3.5.2. Luminescence characteristics and equivalent doses**

427 All investigated quartz samples showed overall acceptable brightness and reproducibility (**Appendix**
428 **B**). However, compared to the samples from Collias, the quartz fine grain (ca 10^6 grains per aliquot)
429 samples from Lautagne appeared rather dim, and additional tests on the coarse grain fraction (ca 10^2
430 grains per aliquot) were not continued due to the low signal intensity.

431 Collias and Lautagne, showed broad D_e distributions but without any obvious pattern. In the case of
432 the samples from Collias this scatter may reflect poor bleaching, dose rate heterogeneities and/or real
433 sediment mixing. The presumed short transport distance from the Rhône Valley may not have
434 yielded a full luminescence signal depletion. More likely, however, post-depositional mixing in

435 conjunction with multiple short-distance erosion and deposition events occurred. Slope-wash and/or
436 creep processes are evidenced by sand-sized and even fine- to medium-gravel sized particles,
437 particularly in the L1L2 unit and the colluvial layer at the bottom of L1L1 at Collias (**Fig. 2**). Intense
438 syn- and post-sedimentary bioturbation is also likely to have been involved.

439 For the samples from Lautagne (**Fig. B6**), the scatter is rather large for fine grain quartz samples with
440 ca 10^6 grains per aliquot and the expected averaging effects. However, the inter-aliquot scatter is
441 dominated by the individual errors. Thus, these aliquots represent a common central dose.

442 **3.5.3. Dose rate results**

443 Th and K concentrations are comparable for the sites Collias and Lautagne (**Appendix B**). In both
444 sites, the Th and K concentrations show a trend towards higher values in the lower Bw horizons
445 (potential Th adsorption on clay particles). We found radioactive disequilibria in the U-decay chain
446 at both sites. However, the onset of these disequilibria could not be determined, leading us to
447 calculate an average value of the U concentration (see **Appendix B**).

448 **3.5.4. Luminescence ages results**

449 The OSL ages obtained for the loess deposits at Collias range from ~100 ka to ~25 ka. Age
450 inversions overlap within uncertainties and are not considered significant. While the general pattern
451 is similar for ages calculated as mean $\pm$ standard error of the mean (**Fig. B11**, displayed in blue) and
452 those using the ‘baSAR’ modelling approach (**Fig. B11**, displayed in red), the Bayesian approach
453 leads to significantly older ages in the lower part of the section. Nevertheless, given the
454 luminescence ages and D_e values close to commonly accepted saturation values for quartz
455 luminescence measured in the UV wavelength region, an age underestimation cannot be excluded,
456 and the values must be interpreted cautiously.

457 The OSL ages obtained for the loess of the Lautagne A sequence range from 31.1 ± 2.4 ka to $7.5 \pm$
458 0.6 ka, and the ages are stratigraphically consistent within uncertainties (**Fig. B12**). **Figure 3** shows

459 that the OSL estimates are consistent with the radiocarbon ages obtained from gastropod shells (see
460 section 3.4.2). Only samples BDX18944 (7.5 ± 0.6 ka) and DeA-18281 (12.1–12.6 ka cal. BP)
461 appear significantly underestimated and were not considered in the Bayesian age model. We assume
462 that this young age reflects the admixture of recent soil material through bioturbation.

463 3.5.5. Radiocarbon ages

464 A total of 27 radiocarbon dates were determined from unit L1L1, including 23 at Lautagne A and 4
465 at Collias (**Table 2**).

466 At Lautagne A, the ages from *Pupilla muscorum* shells appear to be consistent with the stratigraphy
467 and the OSL ages (**Fig. 9B**), while those from earthworm calcite granules show major stratigraphic
468 inversions and younger ages (**Table 2**). The inconsistency of the latter can be explained by the
469 following factors:

470 (i) lack of precise identification of the earthworm species that secreted these granules. [Canti and](#)
471 [Pierce \(2003\)](#) show that some species (e.g., *Apporrectodea icteria*) deposit their granules at some
472 depth, unlike other species (*Lumbricus terrestris* or *L. rubellus*) which preferentially release them on
473 the soil surface. According to these authors, granules larger than 0.4 mm (i.e., the sieve mesh used in
474 this study) can be produced only by a few earthworm species (mostly the genus *Lumbricus*).
475 However, this statement needs to be confirmed as this study was based on current populations in the
476 UK that are known to have smaller body sizes than those in more southerly latitudes, which acted as
477 refuge areas during glacial period ([Mathieu and Davies, 2014](#));

478 (ii) post-depositional movements resulting in granule redistribution along the soil profile.
479 Earthworms commonly transport surface material (coarse sand, leaves, twigs) to the basal chamber
480 of their burrows that can be located at up to 2 m depth ([Canti, 2007](#)). Syn-sedimentary bioturbation
481 by roots may have been also involved.

Consequently, the ages from earthworm granules were excluded from the analysis to build the age-depth model of the sequence. However, only two dates (Ly-21291 and Ly-51292) among the 14 dates obtained from earthworm granules from the primary loess units yielded post-glacial ages. Thus, although the granules were not in a correct stratigraphic location, they provide reliable information on the age of loess deposition as a whole. Therefore, the ages obtained from Lautagne A (**Table 2**) and other loess sections (**Table 3**) were kept to calculate the age distribution of the Rhône Valley loess (see section 4.5.).

3.5.6. *Collias*

The sediment from the upper part of the S1 pedocomplex yielded ages (1σ) between $ca\ 87.1 \pm 6.5\ ka$ and $82.8 \pm 7.2\ ka$ (**Fig. 9A**), suggesting that it was deposited during the Early Glacial. The lower loess (L1L2) was deposited between $82.8 \pm 7.2\ ka$ and $55.1 \pm 4.4\ ka$, i.e. during the Lower Pleniglacial (~MIS 4-very beginning of MIS 3), and the upper loess (L1L1) between $38.5\ ka$ and $<23.8\ ka$, during the Upper Pleniglacial (late MIS 3-MIS 2). The Bwk horizon (L1S1) corresponds to the Middle Pleniglacial (~MIS 3). Discrepancies between ^{14}C and OSL ages at the top of L1L1 prevent an accurate estimation of the end of loess sedimentation.

3.5.7. *Lautagne A*

According to *a posteriori* ages, the L1L1 loess of Lautagne A (4.60 m to 0.95 m depth) accumulated between ~31–18 ka b2k (**Fig. 9B**), during the Greenland Stadials GS-5.2 to GS-2.1 ([Rasmussen et al., 2014](#)). This period was interspersed with the Greenland Interstadials GI-5.1 to GI-2.1, favourable for the genesis of palaeosols. As suggested by the age-depth model provided by *ChronoModel*, the incipient Ag-BC palaeosols within the L1L1 loess likely correlate with the interstadials. The 95.4% confidence interval of the *a posteriori* ages (27.6 – 27.2 ka b2k and 27.7 – 27.3 ka b2k) obtained for the most developed palaeosol P2 overlaps with the interstadial GI-3. With less certainty, P1 may be correlated to GI-2 and P3 to GI-4.

506

507 **4. Discussion**

508 **4.1. Eemian Interglacial and Early Glacial pedocomplex (S1)**

509 The basal pedocomplex S1 at Collias is characterised by intense reddening, high clay content,
510 chemical weathering, decalcification and precipitation of secondary carbonates in the underlying
511 horizon, forming an indurated Ckm horizon (**Fig. 2**). Fe-Mn hypocoatings on the ped faces suggest
512 occasional waterlogging (**Figs. 5C and 6D**). These characteristics are typical of red Mediterranean
513 soils and testify a forest environment with strong seasonal moisture contrast leading to reddening
514 ([Durn et al., 2018](#); [Fedoroff and Courty, 2013](#); [Yaalon, 1997](#)).

515 Considering the uncertainties associated with the OSL ages (82.8 ± 7.2 ka and 87.1 ± 6.5 ka), the
516 material, in which the upper Bwk horizon of the pedocomplex formed, is attributed to the Early
517 Glacial (MIS 5a-d). The underlying Bw and Ckm horizons can thus be correlated with the Last
518 Interglacial (Eemian, MIS 5e) (**Figs. 2 and 9A**).

519 **4.2. Lower Pleniglacial colluvium and bedded calcareous sandy loess (L1L2)**

520 The Lower Pleniglacial started with the emplacement of loessic colluvium, comprising scattered
521 gravel and reddish lenses containing charcoal fragments (**Fig. 3**). The colluvium reflects reworking
522 of the red Interglacial/Early Glacial Bw horizons exposed along the slope.

523 Then, increased aridity and wind intensity led to the deposition of coarse-grained calcareous loess
524 that has been redistributed and sorted by slopewash during rainstorm and/or snowmelt (**Figs. 3 and**
525 **8A**). The coarse texture indicates abundant sand transport from the sources, probably from the bed of
526 the Rhône River ([Bosq et al., 2020](#)) since the particle size of the aeolian deposits becomes coarser
527 towards this river (**Fig. 1B**). The presence of lenses of calcareous rock debris (**Fig. 4A, 4B**) indicates

active frost weathering of limestone outcrops. Slope wash during rainstorms or snowmelt during summer are thought to be the main factor involved in the deposition of these lenses.

The OSL ages around 55 ka (BDX21325: 55.5 ± 4.4 ka and BDX21326: 55.1 ± 4.1 ka) suggest that loess deposition took place during late MIS 4 and/or the very beginning of MIS 3 (**Fig. 9A**). These periods are characterised by an increase in dust concentration in the Northern Hemisphere records, including the Greenland ice record (NGRIP; [Ruth et al., 2003](#)) and the Eifel Laminated Sediment Archive (ELSA) lake record in Germany ([Seelos et al., 2009](#); [Sirocko et al., 2016](#)).

4.3. Middle Pleniglacial brown Bwk horizon (L1S1)

The brown Bwk horizon shows slight dissolution of carbonates, increased clay content and an increase in the concentration of pedogenic ultrafine magnetic grains. The lack of significant variation of weathering indices (CPA, Rb/K) indicates moderate silicate weathering (**Fig. 2**). Large rhizoliths formed below due to carbonate leaching and reprecipitation. The carbonate rhizoliths within the brown horizon must result from an interplay between pedogenesis and moderate loess accumulation rates. Thereby, the loess input led to an upward movement of the soil surface and addition of primary carbonates, whereas pedogenesis involved leaching of these fresh inputs and accumulation of secondary carbonates within the lower part of the brown horizon (**Fig. 4B**). Thus, this brown Bwk horizon implies a decrease (possibly multiphased) in loess sedimentation and a moister climate favourable to the development of vegetation. The soil has been truncated by erosion and covered by colluvial material.

According to our chronological data, the soil to which the truncated Bwk horizon belonged formed between 55.1 ± 4.1 ka and 38.5 ± 2.5 ka (**Fig. 9A**), i.e. within a long interval during MIS 3.

4.4. Upper Pleniglacial loess (L1L1)

4.4.1. Loess deposits

551 The L1L1 loess reaches more than 2 m thickness at Collias and 4 m at Lautagne A (**Fig. 4**). Similar
552 homogeneous yellowish, up to 5 m thick loess deposits were observed in many outcrops along the
553 Rhône Valley (Bosq et al., 2018). They share common characteristics with the loess of the southern
554 part of the Carpathian basin (e.g., Antoine et al., 2009b; Bokhorst et al., 2011; Marković et al., 2009;
555 Novothny et al., 2011), including (i) coarse texture, (ii) lack of well-developed palaeosols; (iii)
556 absence of structures of periglacial origin (ice-wedge pseudomorphs, soil wedges) except for platy
557 microstructure; (iv) absence of laminated deposits of niveo-aeolian origin such as those commonly
558 observed in NW Europe (Antoine et al., 2016; Lehmkuhl et al., 2016; Zens et al., 2018) and (v)
559 abundant syn-sedimentary bioturbation.

560 The EM-1 subpopulation, which is predominant in the samples from Lautagne A (**Fig. 8B**), indicates
561 a relatively limited transport distance, in the order of a few kilometres to tens of kilometres. This
562 fraction originates from the Rhône riverbed, where the particles derived from the AIS were subjected
563 to deflation. Riparian vegetation was probably involved in the trapping of wind-transported particles
564 (e.g., Bosq et al., 2018).

565 The GSI peaks are interpreted as reflecting periods of increasing wind carrying capacity (Antoine et
566 al., 2009a; Schirmer, 2016; Vandenberghe et al., 1985). According to the chronological data of
567 Lautagne (**Fig. 9B**), the highest GSI values occurred during GS-3 and GS-4, whereas they slowly
568 decreased during GS-2.1 (**Fig. 3**).

569 4.4.2. *Incipient palaeosols*

570 Weakly developed palaeosols (P1 to P3) are visible within the L1L1 loess at Lautagne A (**Fig. 3**).
571 The Ag horizons are finer-grained than primary loess. They exhibit hydromorphic features and low
572 organic matter content. The abundant carbonate concretions are interpreted as resulting from
573 secondary carbonate precipitation during the accumulation of overlying loess, favoured by the fine-

574 grained texture. The BC horizons have higher clay content, slight carbonate depletion and a slightly
575 darker and reddish colour.

576 Their genesis indicates short periods of decrease or cessation of loess sedimentation due to milder
577 climate. The hydromorphic features in the topsoils can be explained by two hypotheses, which are
578 not mutually exclusive:

579 (1) The soils developed during a period of climatic improvement associated with increased
580 precipitation and snow accumulation. Waterlogging in the topsoil resulted from snow cover and
581 subsequent snowmelt above still frozen ground that did not allow for meltwater infiltration.
582 Permafrost was absent in the southern part of France during the coldest periods of the Pleistocene
583 ([Andrieux et al., 2016](#)) and waterlogging occurred only during limited periods each year.

584 (2) Reducing conditions in the topsoil horizon occurred upon burial, as a consequence of soil organic
585 matter degradation by soil microorganisms. Unlike the humic horizons described in the loess sections
586 of continental Eastern Europe (e.g., [Veres et al., 2018](#)), soil-forming conditions in less continental
587 regions led to the formation of poorly condensed organic matter with low "black carbon" content
588 ([Eckmeier et al., 2007](#); [Schmidt and Noack, 2000](#)), which was less resistant to degradation.

589 **4.5. Regional chronology**

590 In addition to the ages obtained in this study, we compiled the ages available for the loess deposits in
591 southeast France from the literature to assess the chronology of the main regional sedimentation
592 phases. Overall, 21 OSL dates on quartz and 43 ¹⁴C dates on gastropod shells, earthworm granules
593 and charcoal were selected (**Tables 1 to 4**). The age distribution was calculated using the Kernel
594 Density Estimation (KDE) ([Vermeesch, 2012](#)), which helps to identify how ages cluster. The clusters
595 provide a chronological estimate of the main periods of dust accumulation, assuming that sampling
596 was equally distributed throughout the loess sequences. Although the analysis must be considered
597 preliminary because of the limited number of available dates (N=64), the comparison of the KDE

graph with the modelled AIS volume (expressed in metres of sea level equivalent) (Seguinot et al., 2018) together with the Rhine (Preusser et al., 2011) and the Tagliamento (Monegato et al., 2007) glacial systems for which robust chronological constraints are available on the one hand, and the dust concentration recorded in the NGRIP ice core (Ca^{2+} in ppb) on the other hand, lead to the following conclusions (**Fig. 10**):

- (1) For the period before ca 40 ka, only a few dates (N=5) are available, which suggests weak dust accumulation. Surprisingly, no age falls with certainty into MIS 4, a cold period that was marked by substantial AIS development. The reason behind remains unclear (weak deposition, subsequent erosion, loess recycling ?).
- (2) For the Upper Pleniglacial, the age distribution shows an approximate synchronicity between loess deposition and AIS fluctuations. The peak of loess ages at 28–24 ka, i.e. GS-3, coincides with the maximum AIS volume (26–23 ka, Ivy-Ochs et al., 2018; Luetscher et al., 2015; Monegato et al., 2017; Preusser et al., 2011; Seguinot et al., 2018) and the highest CSI values. This period includes Heinrich Event 2 (HE-2, Sanchez Goñi and Harrison, 2010), which was responsible for cold and arid conditions on the European continent (Duprat-Oualid et al., 2017; Fletcher et al., 2010).
- (3) During the late Last Glacial Maximum (late LGM) (ca 23–19 ka, Clark et al., 2009), the AIS entered a recessional phase and lost 80% of its volume at 17.5 ka (Ivy-Ochs et al., 2008; Monegato et al., 2017). Following the deglaciation during GS-2, a significant glacial re-advance (not visible in the simulation) occurred during the Gschnitz stadial at 17–16 ka, in response to the HE-1 cooling (Ivy-Ochs et al., 2006, 2008; Ivy-Ochs, 2015). Accordingly, the age density decreases sharply during GS-2, while aeolian accumulation may have resumed somewhat during HE-1. Overall, GSI values gradually declined over this period.
- (4) The aeolian activity persisted until the Younger Dryas cooling (GS-1) at 12.9–11.7 ka.

These preliminary results suggest that the peak of dust accumulation in the Rhône Valley was concomitant with the maximal AIS extension. The link between these two phenomena could reside in the modulation of the amount of glacially abraded fine particles by the advances and retreats of the ice sheet. These particles, which were transported by the Rhône River and its tributaries, and then remobilised by deflation, formed the main source of dust as shown by [Bosq et al. \(2020\)](#).

Therefore, glacier dynamics was probably the primary factor influencing loess deposition, whereas millennial climate fluctuations (HEs), including periods of enhanced dryness and associated changes in vegetation acted as a modulator of the primary signal.

5. Conclusions

The high-resolution multi-proxy sedimentological and chronostratigraphical analysis of two loess sections in the Rhône Valley allow to draw the following conclusions:

- (1) A ~8 m thick loess record of the Last Climate Cycle is preserved at Collias. Loess deposition occurred during the Lower and Upper Pleniglacial (L1L2 and L1L1). The loess overlies a thick red pedocomplex (S1) developed during the Last Interglacial and the Early Glacial, similar to those observed elsewhere in southern and southeastern Europe (e.g., [Durn et al., 2018](#); [Fedoroff and Courty, 2013](#)). A brown Bwk horizon (L1S1) developed during the Middle Pleniglacial. In the Lautagne section, the ~ 5 m thick loess deposits provide a detailed record of the Upper Pleniglacial.
- (2) The chronological data (AMS ^{14}C and OSL) show that the main phase of loess deposition (L1L1) corresponds to the stadials GS-5 to GS-2. The loess is coarse, calcareous and is interspersed with three incipient palaeosols at Lautagne A. These palaeosols are correlated with the Greenland Interstadials GI-4 to GI-2.

(3) At a regional scale, the numerical ages obtained on the upper loess (L1L1) range between ca 38.5 ka and 12 ka with a main peak at 28–24 ka, which coincides with the maximal AIS advance.

At a European scale, the aeolian systems composed of coversands and loess formed disconnected geographical units, each characterised by specific regional environmental conditions (i.e., regionally varying temperature, precipitation, and vegetation). It thus seems plausible that the phases of aeolian accumulation were not strictly synchronous across Europe, because the controlling factors (i.e., sediment availability, soil moisture, permafrost) varied considerably, both in time and space. This hypothesis remains, however, to be studied in more detail.

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 1170

1171 **List of captions**

1172 Fig. 1: A) Map of aeolian deposits in Western Europe from [Bertran et al. \(2016\)](#) with additional data
 1173 from [Bosq et al. \(2018\)](#) and [Lindner et al. \(2017\)](#), showing the location of the sections studied in the
 1174 Rhône Valley and within the Rhône catchment (red line). The British-Irish Ice Sheet (BIIS) and
 1175 Scandinavian Ice Sheet (SIS) are from [Hughes et al. \(2016\)](#). The Alpine Ice Sheet (AIS) and other
 1176 LGM glaciers are from [Ehlers and Gibbard \(2004\)](#). Sea-level drop to 130 m below sea level during
 1177 the LGM is assumed ([Lambeck et al., 2014](#)). Palaeocoastlines are from [Zickel et al. \(2016\)](#). The map
 1178 is based on a Digital Elevation Model (DEM) (ETOPO1; [Amante and Eakins, 2009](#)), ETRS89-
 1179 LAEA projected geographic coordinate system. B) Spatial distribution of aeolian deposits in the
 1180 study area ([Bosq et al. 2018](#)). C, D) Close-up maps of the Collias (C) and Lautagne (D) areas, based
 1181 on a DEM with 5 m resolution from RGE ALTI® (<http://professionnels.ign.fr>). The geological
 1182 formations were redrawn from the 1:50,000 geological map (<http://infoterre.brgm.fr>). Abbreviations:
 1183 Fz=Holocene floodplain, Fy, Fyc-e, Fyb, Fya, Fw, Fv=Pleistocene terraces, Jz=alluvial fans,
 1184 m1v/m2C=Miocene molasses (yellow), n4-5U=Cretaceous limestone, Oe=loess (green),
 1185 U=travertine.

Fig. 2: Detailed stratigraphy of the Collias section with the locations of the samples for sedimentological and micromorphological analysis. Curves: low-frequency mass-specific magnetic susceptibility (χ_{LF}) expressed in $10^{-6} \text{ m}^3/\text{kg}$, frequency dependant magnetic susceptibility (χ_{FD}) expressed in %, grain-size parameters (clay, GSI, coarse fraction), colour reflectance (a^*), geochemical ratios (Si/Al, Ti/Al, CPA, Rb/K, Ca/Al, Fe/Al). Details on luminescence dating results (red) are provided in **Table 1** and on radiocarbon dating results (green) in **Table 2**. The grey bars indicate soil formation.

Fig. 3: Detailed stratigraphy of the Lautagne section (Lautagne A) with the location of the samples for sedimentological and micromorphological analysis. Curves: low-frequency mass-specific magnetic susceptibility (χ_{LF}) expressed in $10^{-6} \text{ m}^3/\text{kg}$, frequency dependant magnetic susceptibility (χ_{FD}) expressed in %, grain-size parameters (clay, GSI, coarse fraction), colour reflectance (a^*), geochemical ratios (Si/Al, Ti/Al, CPA, Rb/K, Ca/Al, Fe/Al). Details on luminescence dating results (red) are provided in **Table 1** and on radiocarbon dating results (green) in **Table 2**. The grey bars indicate soil formation.

Fig. 4: A, B) Photographs of the main lithofacies of Collias with luminescence ages. C) Close-up view of the erosional surface above the rubified pedocomplex (S1) exposed in a roadcut approximately 100 m from the Collias section; D) Overview of the Lautagne section (Lautagne-A) during archaeological excavations; E) Detail of the deformed incipient palaeosol (P2) of Lautagne (Lautagne-B). All the photographs were taken by M. Bosq

Fig. 5: Photographs of selected thin sections (6.5 x 3.0 cm) of the Collias (A, B and C) and Lautagne (D, E and F) sections. A) Brown Bwk horizon around 320 cm depth - channel microstructure with scattered rock fragments showing thin, clayey silt coatings (M3). B) Calcareous sandy loess (L1L2) around 400 cm depth - 3 to 5 cm thick beds of sand and silt, massive to channel microstructure with abundant secondary calcite impregnations; few scattered Fe/Mn nodules (M4). C) Rubified Bw

1210 horizon around 680 cm depth - subangular blocky macroaggregates (one to several centimetres in
 1211 diameter) with completely decalcified reddish groundmass, diffuse Fe/Mn nodules and coatings. At
 1212 the base of the thin section, loose discontinuous infillings with disintegrated excrements of
 1213 enchytraeids or collembolas (M8). D) L1L1 loess near the top of the sequence - channel to vughy
 1214 microstructure with complex packing voids and large abundant loose infillings of voids by
 1215 disintegrated excrements (M8). E) Homogenous loess (L1L1) around 260 cm depth - poorly
 1216 developed subangular blocky structure with carbonate impregnations. In places platy microstructure,
 1217 partly destroyed by bioturbation (M4). F) Ag horizon around 280 cm depth - massive microstructure
 1218 with weakly impregnated orthic Fe-hydroxyde nodules (M3). Abbreviations: cc=carbonate coating,
 1219 ci=carbonate impregnation, cap=clayey silt capping, e=organo-mineral excrements, inf=infilling,
 1220 Io=amorphous Fe-Mn hydroxides, n=Fe-Mn nodule, pl=platy microstructure R=rock fragment.

1221 Fig. 6: Microfacies details of selected samples from Collias (A, B, C and D) and Lautagne A (E, F, G
 1222 and H) sections (see **Figs. 2** and **3**) (plane-polarized (PPL)). A) L1L1 loess around 90 cm depth -
 1223 dense incomplete micritic infillings and hypocoatings, and loose infilling of channels by porous
 1224 organio-mineral microaggregates (M1). B) Brown Bwk horizon around 320 cm depth - earthworm
 1225 granule showing radially arranged sparite crystals (M3). C) Calcareous sandy loess (L1L2) around
 1226 400 cm depth - calcite hypocoating around channel (M4). D) Rubified Bw horizon around 680 cm
 1227 depth - Fe-Mn hypocoatings and quasicoatings (M8). E) L1L1 loess around 110 cm depth -
 1228 earthworm granules (M7). F) Homogenous loess (L1L1) around 170 cm depth - calcitic
 1229 impregnation (M6). G) Homogenous loess (L1L1) around 260 cm depth - platy microstructure (M4).
 1230 H) Ag horizon around 280 cm depth - crescent fabric in silty groundmass, resulting from
 1231 bioturbation by soil mesofauna (M3). Abbreviations: ci=carbonate impregnation, e=organo-mineral
 1232 excrements, eg=earthworm granule, Hc=calcite hypocoating, Io=amorphous Fe-Mn hydroxides.

1233 Fig. 7: Grain-size distribution of the samples from Collias (A) and Lautagne A (B). The upper limits
 1234 of the grain-size classes used here are: 8 μm for clay and 56 μm for silt. C) End-member modelling

1235 results of the grain-size dataset of both sections. The main modes of the three end-members were
1236 determined by parametric curve-fitting using the R package ‘mixdist’ (Macdonald and Du, 2015).

1237 Fig. 8: Contribution of the three end-members and coefficient of determination (R^2) for each sample
1238 from the sections Collias (A) and Lautagne A (B).

1239 Fig. 9: Chronological data. A) Distribution of the OSL and radiocarbon ages of the section Collias
1240 obtained in this study. B) Posterior distribution (95%) of the ages for each sample derived from the
1241 Bayesian age model of the Lautagne section using *ChronoModel*. The OSL ages are generally
1242 consistent with the ^{14}C ages, although they have large error bars. Greenland interstadials from the
1243 NGRIP record on the GICC05 age model (Rasmussen et al., 2014) are indicated in orange.

1244 Fig. 10: A) Total AIS ice volume through the Last Glacial cycle (100–10 ka) from a recent
1245 simulation using the Parallel Ice Sheet Model (PISM) with climate forcing derived from WorldClim
1246 and the ERA-Interim reanalysis (Seguinot et al., 2018). Modelled ice volume is expressed in meters
1247 sea level equivalent (m s.l.e.). Fluctuations of the Rhine (red) (Preusser et al., 2011) and Tagliamento
1248 (purple) (Monegato et al., 2007) glaciers. B) Kernel Density Estimation (KDE) of ages for the OSL-
1249 and radiocarbon-dated loess from the Rhône Valley (this study, Ollivier, 2006; Bazile, 2007;
1250 Magnin, 2014; Varennes et al., 2015; Laroche et al., 2020; Thirault et al., 2020). C) NGRIP Ca^{2+}
1251 curve over the last 100 ka according to the revised Greenland Ice Core Chronology proposed by
1252 Rasmussen et al. (2014). The chronological intervals for the Younger Dryas (YD) period and
1253 Heinrich Events (HEs) are depicted in blue. They are taken from Banks et al. (2019) for HE-3 and
1254 HE-2 and Sanchez Goñi and Harrison (2010) for HE-6, 5, 4 and 1. The chronological limit of each
1255 MIS is also taken from Sanchez Goñi and Harrison (2010).

1256

1257 Table 1: Final dose rates, equivalent (D_e) and luminescence age values of the Collias and Lautagne A
1258 sections. Standard errors are quoted as 1σ , rounded to one digit. Final ages used for this study are
1259 shown in bold numbers. For more details, see the **Appendix B**.

1260 Table 2: AMS radiocarbon ages of samples from the sections Collias and Lautagne A (calibration by
1261 use of *IntCal13*, according to [Reimer et al., 2013](#)). Final ages used for this study are shown in bold
1262 numbers.

1263 Table 3: AMS radiocarbon ages of loess samples from other locations in the Rhône Valley
1264 (calibration by use of *IntCal13*, according to [Reimer et al., 2013](#)).

1265 Table 4: OSL ages of loess samples from other locations.

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A) Collias

B) Lautagne A

Figure

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CRediT Author Statement

Mathieu Bosq: *Conceptualization, Methodology, Writing – original draft, Formal analysis, Investigation, Visualization.* **Sebastian Kreutzer:** *Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Visualization.* **Pascal Bertran:** *Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.* **Jean-Philippe Degeai:** *Investigation, Writing- review & editing.* **Pauline Dugas:** *Investigation, Formal analysis.* **Annette Kadereit:** *Validation, Writing – review & editing.* **Philippe Lanos:** *Formal analysis, Software.* **Olivier Moine:** *Investigation, Writing – review & editing.* **Nora Pfaffner:** *Investigation, Writing – review & editing.* **Alain Queffelec:** *Methodology, Software, Formal analysis, Resources.* **Daniela Sauer:** *Investigation, Writing – review & editing.*