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Chronology of the Late Roman Antiquity walls of Le Mans (France) by OSL, archaeomagnetism and radiocarbon

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1 **Title**

2 Chronology of the Late Roman Antiquity walls of Le Mans (France) by OSL, archaeomagnetism
3 and radiocarbon

4

5

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22

23 **Abstract**

24 The Late Roman Antiquity walls of Le Mans in northwest France are one of the most
25 representative and preserved examples of the urban fortifications that developed in the Roman
26 provinces of Gaul and Germany at this period. Because of a lack of reliable chronological data, the
27 construction of the walls was poorly dated, which made unclear its historical context. The main
28 objective of this study was to reassess the date of construction using several methods on a well-
29 preserved sector (sector 11) of the Late Roman Antiquity walls. The dated masonries, thoroughly
30 studied in building archaeology beforehand, are characterized by an alternating of stone and brick
31 courses. Sampling focused on one hand on mortars with four radiocarbon dates (¹⁴C) and six
32 single-grain optically stimulated luminescence (SG-OSL) dates, and on the other hand on bricks
33 with two OSL dates (quartz fine grain technique) and one archaeomagnetic date on a set of 104
34 bricks. The consistency between the dates on the two types of materials discards a possible reuse
35 of the bricks from former Roman buildings. They were produced for the construction of the walls
36 with the presence of several types of bricks likely reflecting a supply from at least two workshops.
37 The dating program in the sector 11 also included 21 ¹⁴C dates and six SG-OSL on protohistoric
38 structures, Early Empire masonries and large medieval buildings, in order to investigate the
39 evolution of the area over the long-term and to better constrain the chronology of the Late Roman
40 Antiquity walls in Bayesian modelling. The chronological model (Chronomodel software) dates
41 this construction between 301 and 423 CE at 95% of confidence. This date clearly excludes that
42 the Late Roman Antiquity walls were built during the crises of the 3rd century, as previously
43 thought, but rather in the stable political and economic context of the 4th century.

44

45 **Keywords**

46 Chronology; Late Roman Antiquity; urban wall; Gaul; OSL; archaeomagnetic dating; Bayesian
47 modelling

48

49 **1. Introduction**

50 At the Late Roman Antiquity, cities in Roman Gaul underwent important transformations with a
51 gradual decrease of their area from the end of the 2nd century CE and with the construction of
52 walls in most capital cities between the last quarter of the 3rd century and the middle of the 5th
53 century CE. This process is attested throughout the Roman Empire, the city of Rome itself being
54 surrounded by a fortification from 270. In the provinces of Three Gauls and Germanies, the
55 construction of such urban fortification is a new phenomenon, because almost all the capital cities
56 did not have one during the Early Empire period. As elsewhere, it reflects major social and political
57 changes in a context less stable than in the first two centuries CE. The period between ~230 and
58 ~280 was actually characterized by multifaceted and successive crises in Gaul, as in the whole
59 Roman Empire. Main factors were weakening of central power with a dissent in Gaul, coupled
60 with first German incursions, brigandage, revolts, monetary inflation, epidemics and climate
61 change with the end of the Roman Warm period. This troubled period was followed by a takeover
62 of the Empire up to the end of the 4th century with an administrative and military reorganization,
63 mainly by Aurelian (emperor in 270–275) then Diocletian (284–305) and Constantine (306–337),
64 until the end of the 4th century (Sotinel and Virlovet (eds), 2019).

65 In this changing historical context, the reason for the construction of urban fortifications and their
66 role(s) in the cities remains unclear for most of them, because of chronological uncertainties.
67 Building of urban walls were traditionally dated in the last third of the 3rd century, often around
68 270 CE at the climax of the crisis, giving them principally a defensive role. Archaeological
69 excavations performed in several cities (e.g., Amiens, Grenoble, Reims, Tours) indicate that
70 buildings in the Three Gauls and in Germanies occurred in reality over a longer period from the
71 mid 3rd century up to the end of the 4th century. These reassessments suggest that urban walls, at
72 least those built after 270, had also a promoting role of the regained power of the Empire and of
73 the prestige of the city (Bayard and Fourdrin (eds), 2019; Intagliata et al., 2020).

74 This study focuses on one of the most famous examples of Late Roman Antiquity urban
75 fortifications in Gaul, Le Mans in North-West France (48.0°N – 0.2°E) (Bouillet et al., 2022). At this
76 period, the city was the capital of *Aulerici Cenomani* people in the *Gallia Lugdunensis* III province.
77 The Late Roman Antiquity walls, built on a promontory above the Sarthe River, formed a NW-SE
78 quadrangle of circa 500 × 100 meters, enclosing an area of 8.5 hectares (Fig. 1a). They are very
79 well preserved over almost the three-quarters of the perimeter and sometimes over more than
80 10 m high. Their neat architecture is also famous with geometric patterns made by the assembly
81 of different coloured rocks and bricks in the masonries. These characteristics, unique in Gaul, have
82 attracted the interest of researchers since the 19th century. The most comprehensive study was
83 performed by Joseph Guilleux in the 80-90s (Guilleux, 2000). Since, the development of rescue
84 excavations and methodological improvements in building archaeology (e.g., 3D) have justified to
85 resume in 2017 a global study of the walls in the framework of a Collective Research Program
86 (*Projet Collectif de Recherche*) directed by two of us (MM & HM). After a first general study
87 (Meunier and Augry, 2019), this program resulted in several publications (Bouillet et al., 2022;
88 Meunier et al., 2022; Bocquet et al., 2022; Pithon et al., 2022) and an exposition in 2022-2023 at
89 the archaeological museum of Le Mans (Jean-Claude Boulard – Carré Plantagenêt museum).

90 Precising the chronology of the fortification is one of the most important objectives of this project.
91 The building of the Le Mans Late Roman Antiquity walls was previously fixed in 280±15 CE by
92 archaeomagnetism on a set of 45 bricks (Goulpeau, 1985). But this first work suffered from
93 several weaknesses. The main ones are the low number of bricks and the uncertainty on their
94 original context, bringing doubt on its homogeneity and thus on the reliability of the dating (Lanos
95 et al., 2015). The archaeomagnetic method has also considerably improved for 40 years in
96 laboratory measurements, in the precision of reference curves and in the dating process thanks
97 to Bayesian statistics (e.g., Lanos, 2004; Gallet et al., 2009; Le Goff et al., 2020; Brown et al., 2021).
98 Moreover, archaeomagnetism date the production of the bricks and not the construction of the
99 wall itself, while the reuse of materials from older building was assumed common at the Late
100 Roman Antiquity.

101 The main objective of our study is to reassess the date of the construction of the urban walls in
102 the light of recent improvements in dating techniques applied to building archaeology. For a few
103 years, the construction of a masonry can now be directly dated by “single-grain” optically
104 stimulated luminescence (SG-OSL), applied to the quartz grains extracted from lime mortar (e.g.,
105 Goedicke, 2011; Urbanová and Guibert, 2017; Urbanová et al., 2018; Guibert and Urbanová, 2022).
106 Another major step forward is the development of hierarchical Bayesian modelling to synthesize
107 multiple dating results in integration with archaeological information as stratigraphic constraints
108 (e.g., Buck and Millard, 2004; Bronk Ramsey, 2009; Lanos and Dufresne, 2012). Using this
109 statistical approach, we provide here a new estimation of the construction of Le Mans urban
110 fortification thanks to the acquisition of new radiocarbon and SG-OSL dating results on mortars
111 and of new archaeomagnetic and OSL dating results on bricks. This strategy to study both types
112 of materials gives also the opportunity to investigate the possible reuse of older bricks, providing
113 information on the building economy. Such multidisciplinary integrated dating program has
114 already been performed, mostly on religious buildings from the Early Middle Age (e.g., Bailiff and
115 Holland, 2000; Bailiff, 2007; Guibert et al., 2012; Stella et al., 2013; Urbanová et al., 2018, in press;
116 Panzeri et al., 2019, 2020) and more rarely on Roman buildings (Urbanová et al., 2015, 2016), but
117 it is, to our knowledge, unprecedented on Late Roman Antiquity urban fortifications. Finally, our
118 chronological study aims to better define the evolution in time of the Le Mans Late Roman
119 Antiquity walls at the medieval period. In spite of the construction of new buildings leaning on the
120 walls, these one maintained their defensive function through the centuries and no important new
121 fortification was built in Le Mans before the mid-14th at the beginning of the Hundred Year’s war
122 (Bouillet et al., 2022).

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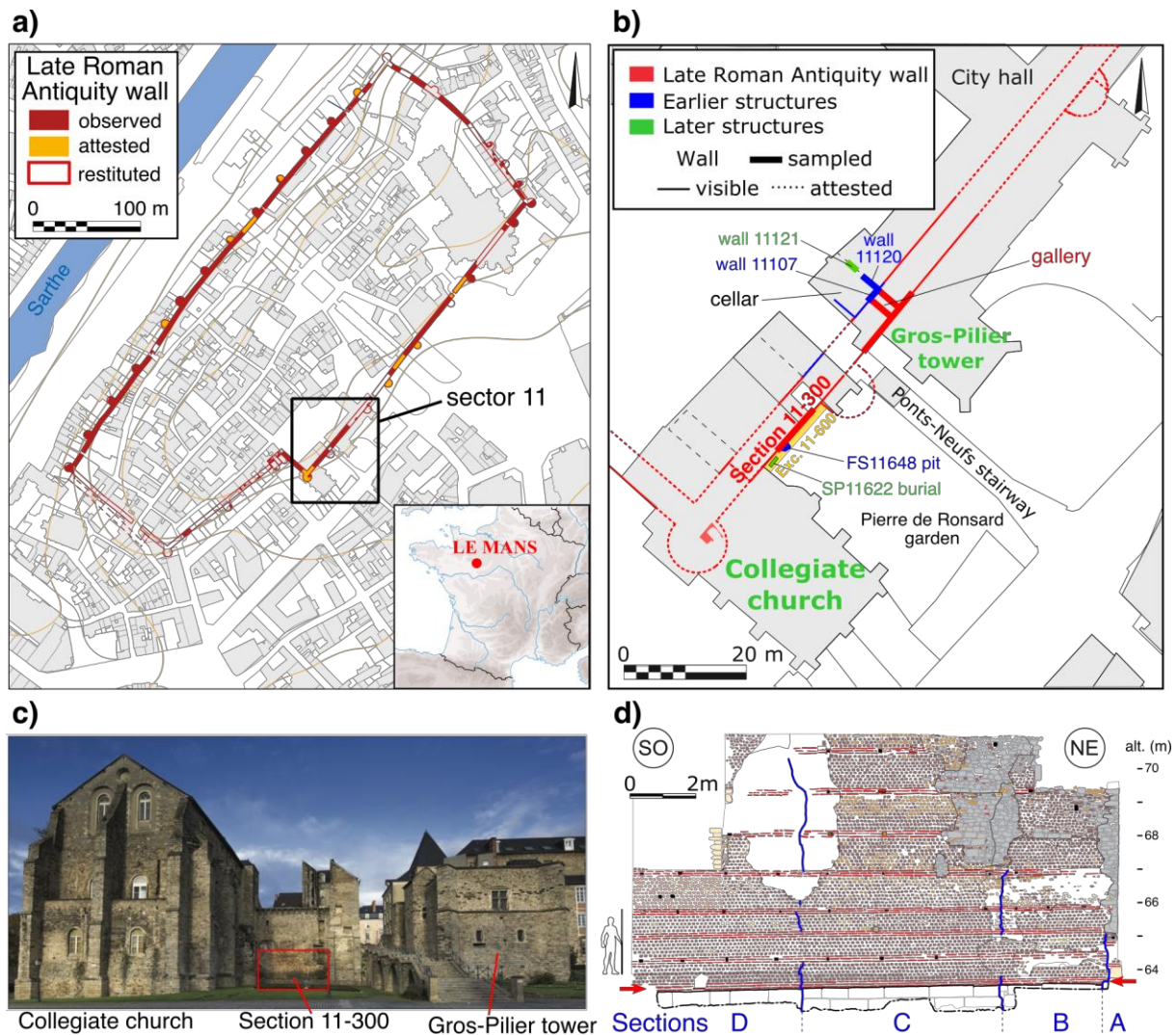
124 **2. Archaeological context**

125 The sector 11 in the south-eastern part of the Roman walls is a key area to fulfil these different
126 objectives (Fig. 1b-c). It has the advantage to present a well-preserved section of the Late Roman
127 Antiquity urban fortification, a few Early Empire architectural remains and large medieval

128 buildings belonging to the former residence and collegiate church of the Counts of Maine, which
129 allows to investigate the evolution of this area over the long term (Meunier and Monteil, 2019a,
130 2020; Bouillet et al., 2022). The absence of large restoration and an easy access to the different
131 buildings also facilitated the detailed study of this sector in building archaeology.

132 **2.1 General description of the sector 11**

133 The Late Roman Antiquity urban walls are mainly preserved in the Pierre de Ronsard garden with
134 a courtine, called section 11-300, of almost 15 m in length and 7.5 m in height (Fig. 1d). Smaller
135 portions of the walls are also visible in the cellars of the city hall (Fig. S1a-b-c-d in supplementary
136 material). In this sector, the wall itself is numbered 11108 and its foundations 11109. These
137 foundations are made either with large stone carved blocks likely in reuse from Early Empire
138 buildings as in the section 11-300 (Fig. 1d), or with mixed smaller rubbles in an orange-coloured
139 lime mortar (Fig. S1a). Above, on the facade, the masonry presents an alternating of brick courses,
140 each one composed of three layers, and of rubble courses mainly in a local purple sandstone
141 (“roussard” sandstone) (Fig. S1a-b-d). These materials are embedded in a crushed *terracotta*
142 mortar (i.e., a lime mortar with sand and crushed *terracotta* in frequent use at the Roman period).
143 The inner part of the wall, apparent thanks to the digging of a medieval gallery (GAL11103, Fig.
144 S1b-d), is constituted by “roussard” sandstone rubbles and a few brick fragments embedded in a
145 beige lime mortar (Fig. S1b-d).



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Figure 1: (a) General plan of the Late Roman Antiquity urban fortification at Le Mans. (b) Plan of the sector 11 highlighting sampled walls and structures. (c) View of the sector 11 from South-East i.e. from outside the Roman walls. (d) Drawing of the section 11-300. The red arrows indicate the lowest brick course sampled for the archaeomagnetic study. (From Meunier and Monteil, 2019b, 2020; CAD: H. Meunier)

The courtine 11-300 gives an insight on the building method (Meunier and Monteil, 2019b). Its careful observation revealed that it was constructed in four successive sections, named A-B-C-D, on the entire height of the wall (Fig. 1d). Their connections in the masonry indicate that the sections A and D were the first built, then C and finally B. The used materials and building techniques (position of geometric patterns and putlog holes) slightly differ between sections,

158 suggesting temporary breaks in the construction or the implication of several team workers. Two
159 sizes of bricks are for example observed (Nauleau, 2019). Bricks with a 260 × 320 mm modulus
160 were used in sections B and D, whereas bricks from the section C have a similar thickness (35-40
161 mm) but a larger 280 × 380 mm modulus. This spatial distribution can be explained by a supply
162 at different workshops or by the reuse of one type of bricks. As the size of brick seems to decrease
163 through the Roman period in Gaul (e.g., De Filippo, 2004; Nauleau, 2013), one could especially
164 wonder if bricks of large modulus were not collected on an older building for the construction of
165 the courtine.

166 Actually, remnants of buildings older than the fortification are present nearby. Two portions of
167 walls, named 11107 and 11120, can be observed in the cellar of the city hall (Fig. S1b-c-d). The
168 analysis of their lime mortar shows that they belonged to two different construction stages or to
169 two different buildings. According to building archaeology, the wall 11120 is, likely slightly,
170 posterior to the wall 11107. These two walls likely date from the Early Empire period and were
171 associated to a public building. A short portion of a third wall, 11121, is also visible in this cellar
172 (Fig. S1b). A modern door prevents to know its temporal relationships with the walls 11107 and
173 11120 as well as with the Late Roman Antiquity urban fortification. The archaeological
174 interpretation suggests that this wall 11121 is more recent than the fortification, but this
175 hypothesis requires confirmation and, in this study, we consider that its date is undetermined.

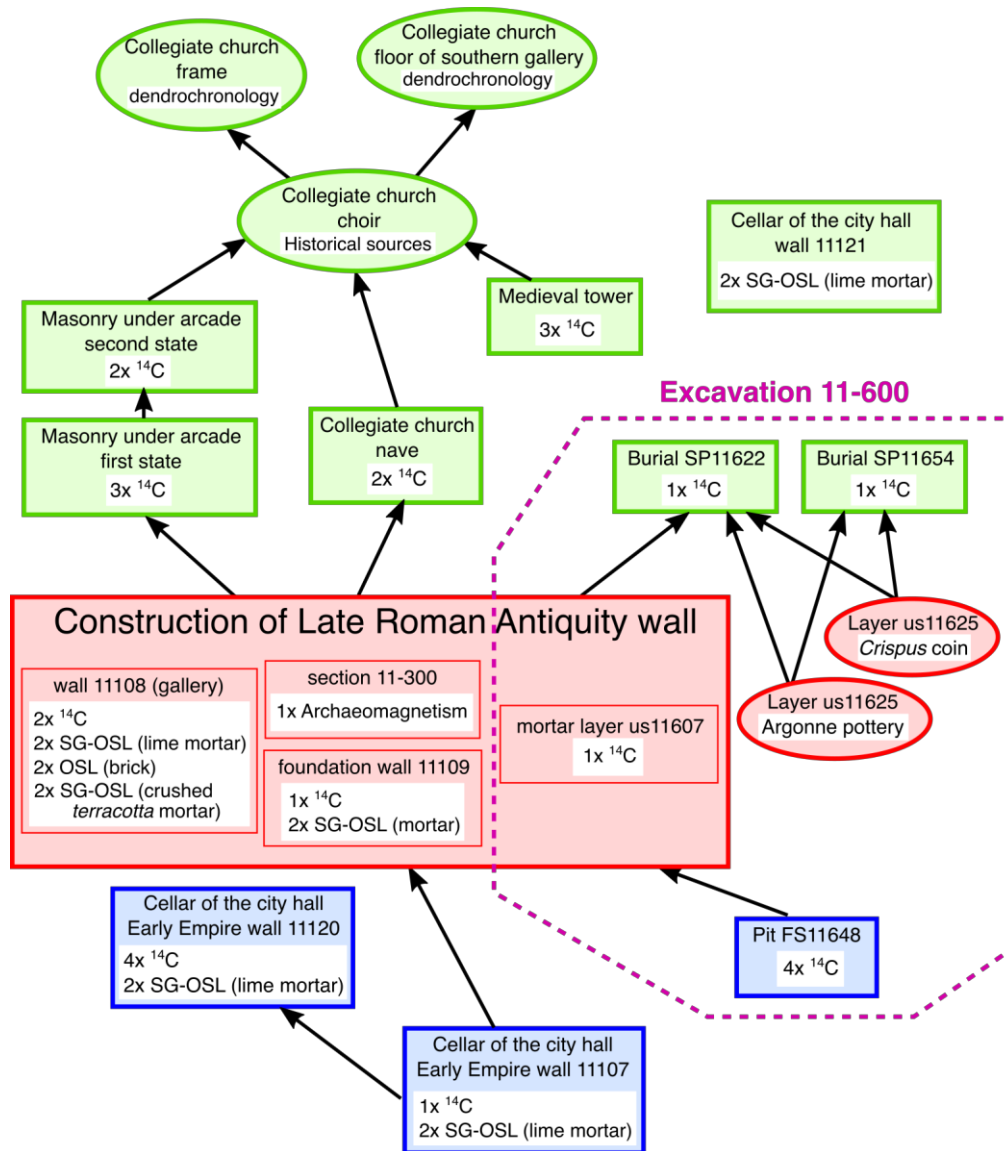
176 In the sector 11, the medieval period was characterized by the construction of the Counts of Maine
177 residence, at the location of the modern city hall and whose main remains are today the Gros-
178 Pilier tower and the Saint-Pierre-de-la-Cour collegiate church (Fig. 1c). While the Gros-Pilier
179 tower was built in the 15th century, the chronology of the collegiate church is less well-known. Its
180 most recent parts, the choir, was built in the 13th-14th centuries as indicated by historical sources
181 and dendrochronology. Conversely, the building of the nave, a tower and an arcade overlain by
182 the choir did not have any dating elements until recently (Meunier and Monteil, 2019a).

183 Besides building archaeology investigations, the occupation of the area is known by an excavation
184 (excavation 11-600) performed in 2019 at the base of the courtine 11-300 (Fig. 1b) (Meunier and
185 Monteil, 2020). The deepest stratigraphic feature is a pit or a ditch (FS11648) of which the
186 absence of Roman ceramics in the filling layers suggests a protohistoric dating. This pit is covered
187 by backfill layers and by a circulation layer dated in the beginning of the 1st century CE. The
188 stratigraphic unit above is an *in-situ* layer of crushed *terracotta* mortar related to the construction
189 of the Late Antiquity walls. The absence of layers between the mortar unit and the 1st century
190 backfill layers reflects earthwork immediately before the construction. The mortar layer does not
191 appear eroded and the deposition of a short sequence of dark earth (unit 11625) just above likely
192 occurred shortly after the construction of the fortification. Very interestingly, this unit 11625
193 contained two dated artefacts, first a Crispus coin, a *nummus* coin minted at Lyon in 318-319
194 (pers. comm. Gérard Aubin). The second artefact is a rim of a Chenet 320 cup in Argonne sigillata
195 dated in the middle or the second half of the 4th century (pers. comm. Christian Le Boulaire). Just
196 below the modern soil, the stratigraphy ends by two Early Middle Age burials (SP11622 and
197 SP11654) (Meunier and Monteil, 2019b, 2020, 2021; Bouillet et al., 2021).

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199 **2.2 Dating strategy**

200 The dating strategy was defined to optimize Bayesian chronological modelling. The Late Roman
201 Antiquity wall was the most sampled structure, because the reassessment of its construction
202 constituted the main objective of the study. Mortars were dated by SG-OSL on quartz grains and
203 by radiocarbon on charcoal inclusions. Bricks were also studied for archaeomagnetic and
204 multigrain OSL dating. Unlike dates on mortars, these methods do not date the construction but
205 the production of the bricks and the comparison between the two materials allows to investigate
206 the possibility of a reuse of bricks from older buildings. In order to better understand the course
207 of the construction, we sampled the wall itself (wall 11108), its foundations (wall 11109) and the
208 different sections of the courtine 11-300.



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211 Figure 2: Simplified stratigraphic diagram of studied contexts with the number of obtained dates.

212 The diagram reproduces the formalism of Chronomodel software (Lanos and Dufresne, 2019).

213 Rectangular boxes correspond to dated events, while circular boxes indicate *Termini Ante Quem*214 and *Post Quem* (called bounds in Chronomodel). The structures related to the construction of the

215 Late Antiquity Roman wall are in red, those before the construction in blue and those posterior to

216 the construction in green.

217

218 As the precision of a Bayesian model is improved by the integration of anteriority or posteriority

219 relationships, dating was not limited to the Late Roman Antiquity wall but also considers earlier

220 and medieval buildings, as well as structures of the excavation 11-600. In total, our experimental
221 work includes 25 radiocarbon dating (22 on charcoals and 3 on bones), 12 SG-OSL dating on
222 mortars, two OSL dating on bricks and one archaeomagnetic dating on a large set of bricks. The
223 sampled contexts are summarized in the Table 1 and Figure 2 together with other chronological
224 information available in the sector 11 provided by stratigraphy, dendrochronology and historical
225 sources. The location of samples is presented in Figures S1 and S2 in supplementary material.

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230 Table 1: Summary of chronological data. Context: location of the sample; Dating method; Dated
231 material or artefact; Laboratory number of the sample for physical dating techniques; Results
232 before calibration for physical dating techniques: uncalibrated age with 1σ standard deviation for
233 ^{14}C , age in years before year of measurement with 1σ standard deviation for OSL, average
234 inclination with radius of the 95% confidence circle (α_{95}), precision parameter (k) and number of
235 bricks for archaeomagnetism; Date intervals.

Context	Method	Material	Lab. number	Results	Intervals (Cal yrs CE)
After construction of the Late Roman Antiquity wall					
Collegiate church, floor of southern gallery in the choir	Dendrochronology	wood	DT-2019-072		1487-1488
Collegiate church, frame of the choir	Dendrochronology	wood	DT-2019-072		1330-1334
Collegiate church, choir	Historical sources				after 1267
Collegiate church, nave	¹⁴ C	charcoal	Lyon-14077(RICH)	1045±30 BP	[897; 922] (8%), [953; 1036] (87%)
	¹⁴ C	charcoal	Lyon-14078(RICH)	1056±30 BP	[896; 924] (14%), [950; 1031] (81%)
Medieval tower	¹⁴ C	charcoal	Lyon-15767(GrM)	970±30 BP	[1022; 1158] (95%)
	¹⁴ C	charcoal	Lyon-15768(GrM)	1040±30 BP	[897; 922] (6%), [953; 1039] (89%)
	¹⁴ C	charcoal	Lyon-15769(GrM)	965±30 BP	[1024; 1158] (95%)
Masonry under arcade, second state	¹⁴ C	charcoal	Lyon-15773(GrM)	965±30 BP	[1024; 1158] (95%)
	¹⁴ C	charcoal	Lyon-15774(GrM)	1030±30 BP	[900; 917] (3%), [975; 1047] (87%), [1084; 1147] (5%)
Masonry under arcade, first state	¹⁴ C	charcoal	Lyon-15570(GrM)	940±30 BP	[1029; 1174] (95%)
	¹⁴ C	bone fragment	Lyon-15571(GrM)	1170±30 BP	[775; 899] (73%), [917; 974] (22%)
	¹⁴ C	charcoal	Lyon-15572(GrM)	970±30 BP	[1022; 1158] (95%)
Excavation 11-600, burial SP11622	¹⁴ C	bone	Lyon-17993(GrM)	1445±30 BP	[574; 651] (95%)
Excavation 11-600, burial SP11654	¹⁴ C	bone	Lyon-17994(GrM)	1090±30 BP	[891; 996] (87%), [1003; 1020] (8%)
Undetermined period, cellar of the city hall, wall 11121	SG-OSL	lime mortar	BDX22226	2629±175 (meas. in 2019)	-610±175 (1σ)
	SG-OSL	lime mortar	BDX22227	1973±179 (meas. in 2019)	46±179 (1σ)
Associated to construction of the Late Roman Antiquity wall					
Late Roman Antiquity wall, gallery between the cellar of the city hall and the Gros-Pilier tower room, wall 11108	¹⁴ C	charcoal	Lyon-14074(RICH)	1675±30 BP	[257; 282] (12%), [328; 433] (81%), [467; 473] (1%), [518; 528] (1%)
	¹⁴ C	charcoal	Lyon-14075(RICH)	1750±30 BP	[240; 402] (95%)
	SG-OSL	lime mortar	BDX22216	1553±173 (meas. in 2019)	466±173 (1σ)
	SG-OSL	lime mortar	BDX22217	1553±128 (meas. in 2019)	466±128 (1σ)
	OSL	brick	BDX22220	1762±107 (meas. in 2019)	257±107 (1σ)
	OSL	brick	BDX22221	1621±92 (meas. in 2019)	398±92 (1σ)
	SG-OSL	crushed <i>terracotta</i> mortar	BDX22218	2139±162 (meas. in 2019)	-120±162 (1σ)
	SG-OSL	crushed <i>terracotta</i> mortar	BDX22219	2207±170 (meas. in 2019)	-188±170 (1σ)
Late Roman Antiquity wall, Gros-Pilier tower room, foundation wall 11109	¹⁴ C	charcoal	Lyon-14076(RICH)	1697±30 BP	[255; 286] (19%), [325; 418] (76%)
	SG-OSL	lime mortar	BDX22222	1648±162 (meas. in 2019)	371±162 (1σ)
	SG-OSL	lime mortar	BDX22223	1526±301 (meas. in 2019)	493±301 (1σ)
Late Roman Antiquity wall, section 11-300	Archaeomagnetism	brick	72181E_REN-2019-3	Inc=62.5° (63.2° at Paris), α ₉₅ =1.6°, k=226, N=35	[31; 157] (51%), [348; 456] (44%)
Excavation 11-600, mortar layer associated to the construction of the wall, us11607	¹⁴ C	charcoal	Lyon-17920(GrM)	1755±30 BP	[237; 401] (95%)
Excavation 11-600, layer us11625	Arch. artefact	<i>Crispus</i> coin			after 318-319
	Arch. artefact	Argonne ceramic			after 300
Before construction of the Late Roman Antiquity wall					
Early Empire structure, cellar of the city hall, wall 11120	¹⁴ C	charcoal	Lyon-15776(GrM)	1960±30 BP	[-40; 128] (95%)
	¹⁴ C	charcoal	Lyon-15777(GrM)	1975±30 BP	[-39; 121] (95%)
	¹⁴ C	charcoal	Lyon-15778(GrM)	1905±30 BP	[61; 217] (95%)
	¹⁴ C	charcoal	Lyon-15779(GrM)	1885±30 BP	[80; 99] (7%), [108; 234] (88%)
	SG-OSL	lime mortar	BDX22224	1780±161 (meas. in 2019)	239±161 (1σ)
	SG-OSL	lime mortar	BDX22225	1920±145 (meas. in 2019)	99±145 (1σ)
Early Empire structure, cellar of the city hall, wall 11107	¹⁴ C	charcoal	Lyon-14073(RICH)	1895±30 BP	[69; 225] (95%)
	SG-OSL	lime mortar	BDX22214	1800±114 (meas. in 2019)	219±114 (1σ)
	SG-OSL	lime mortar	BDX22215	1811±155 (meas. in 2019)	208±155 (1σ)
Excavation 11-600, Pit FS11648	¹⁴ C	charcoal	Lyon-17916(GrM)	2470±30 BP	[-764; -465] (93%), [-434; -421] (2%)
	¹⁴ C	charcoal	Lyon-17917(GrM)	2435±30 BP	[-748; -634] (29%), [-588; -406] (66%)
	¹⁴ C	charcoal	Lyon-17918(GrM)	2460±30 BP	[-755; -415] (95%)
	¹⁴ C	charcoal	Lyon-17919(GrM)	2460±30 BP	[-755; -415] (95%)

237 **3. Laboratory methods**

238 **3.1 Radiocarbon**

239 Most sampled charcoals (18/22) were included in mortar, others coming from the pit FS11648 in
240 the excavation 11-600. Three bones were also dated, one included in the mortar of a medieval
241 masonry and two from the burials SP11622 and SP11654 in the excavation 11-600. Almost all
242 charcoals were first studied in anthracology by Aline Durand at the university of Le Mans. It
243 highlights the predominant use of beeches and oaks in the production of the lime used in mortar
244 making (Tab. S1 in supplementary material). Charcoals from young woods were preferentially
245 selected for dating, in order to break free from old wood effect or at least minimize it. All the
246 samples were prepared in Lyon. The charcoals were pre-treated by the classical acid-alkali-acid.
247 The collagen of bones was extracted by the modified Longin method (Brown et al., 1988) after
248 verification of its good preservation (Schoeninger et al., 1989) and assessment of the possible
249 presence of carbon contamination (Drucker, 2001). Samples were then sent in the form of gas
250 (CO₂) in sealed ampoules to Groningen (Netherlands) and Brussels (Belgium) laboratories where
251 they were graphitized and measured by accelerator mass spectrometry (AMS). Conventional ¹⁴C
252 ages were calibrated with IntCal20 curve (Reimer et al., 2020).

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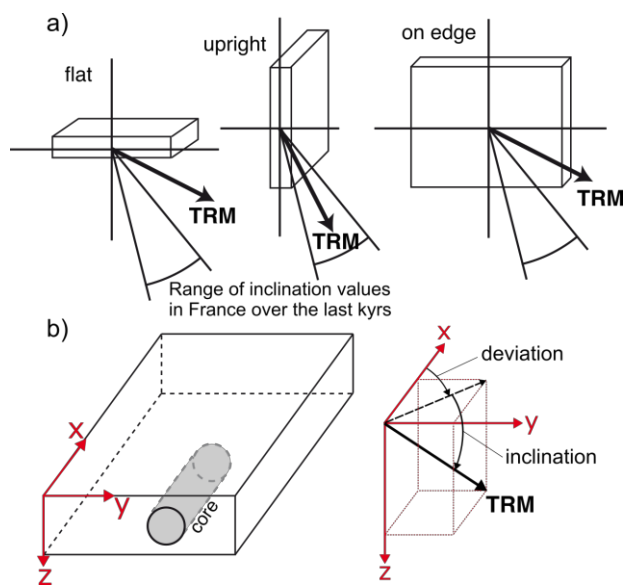
254 **3.2 Archaeomagnetism**

255 Bricks acquired their thermoremanent magnetization (TRM) at the time of their last cooling from
256 high temperature that is during their baking. Even if the precise location of the brick workshop(s)
257 is unknown, the presence of exploitable clay deposits suggests that bricks were likely produced
258 within 30 km from the city (Nauleau, 2021). For archaeomagnetic dating, we considered that the
259 bricks were produced at Le Mans. Bricks were also baked in a different position than the one in
260 the masonry, which means that only the archaeointensity of the geomagnetic field is theoretically
261 preserved. However, in the case of parallelepipedal architectural baked clays as bricks, it is
262 possible to recover the inclination under several hypothesis (Lanos, 1987, 1994). For the sake of

263 convenience and optimized storage inside the kiln, the first one is a disposition of the bricks on
 264 one of their planar sides during the baking, i.e. flat, upright or on the edge (Fig. 3a). On the
 265 assumption that the kiln floor was horizontal, the initial inclination is therefore preserved in one
 266 of these three positions. Only one provides an inclination value in agreement with the secular
 267 variation observed in France over the last millennia (50-75°, see e.g., Hervé and Lanos, 2018; Le
 268 Goff et al., 2020). It is therefore considered that the brick acquired its TRM in this position, making
 269 archaeomagnetic dating possible with the corresponding inclination value (Lanos, 1990). This
 270 approach also provides information on the arrangement of the bricks in the kiln (Lanos, 1994).

271 Here, the archaeomagnetic dating of the bricks from Le Mans Late Antiquity wall is based on the
 272 inclination. We could also study the archaeointensity but this parameter has a low chronological
 273 potential during the first half of the first millennium CE because the geomagnetic field strength
 274 did not vary significantly at this period in Western Europe (e.g., Gomez-Paccard et al., 2016;
 275 Rivero-Montero et al., 2021).

276



277

278 Figure 3: (a) In the hypothesis of a baking of the brick on one face, only one of the three possible
 279 positions provides an inclination value in agreement with the secular variation in France over the

280 last millennia (from Lanos, 1994). (b) Orientation of the archaeomagnetic specimens within the
281 brick and directional components of the TRM in this coordinate system.

282

283 In order to take account for the uncertainties on the estimation of the inclination (for example the
284 fact that bricks are not perfectly horizontal or vertical on the kiln floor), a large number of
285 individual bricks, at least 50, is necessary (Lanos, 1994). The set of bricks must also appear
286 homogeneous in terms of size and composition. The part of the Late Roman Antiquity wall that
287 best met the criteria of number and homogeneity of bricks is the section 11-300 in the Pierre de
288 Ronsard garden (Fig. 1d). Sampling focused on the lowest brick course, the best preserved, just
289 above the large limestone blocks of the wall foundation and basement. 104 different bricks were
290 sampled with 30, 49 and 25 bricks in the sections B, C and D respectively (Fig. S2a in
291 supplementary material). The section A, visible over only a short length, was not studied. The
292 extensive sampling allows to test the possibility of chronological differences between the bricks
293 of the three sections and between the large (section C) and smaller (sections B+D) moduli, as well
294 as the possibility of reuse of one of these subsets of bricks. In each brick, a core, one inch in
295 diameter and 5-10 cm long, was drilled perpendicularly to the visible side using an electrically-
296 powered device (Fig. S2b-c). After sampling, holes were finally filled by a self-made mortar of
297 similar colour to the brick (Fig. S2d).

298 All experiments were performed at Rennes palaeomagnetic laboratory. First, cores were cut in
299 22-mm-long standard specimens (2 or 3 per core). Low-field susceptibilities were measured with
300 a Bartington MS2 susceptibility meter and the remanent magnetizations with a Molspin spinner
301 magnetometer. The direction of the magnetization was defined in a coordinate system relative to
302 the brick (Fig. 3b). In this system, inclination is the angle between the TRM and the surface of the
303 brick. The angle between the horizontal component of the TRM and the length of the bricks is
304 called deviation. The direction of the TRM was determined after stepwise thermal
305 demagnetization on one specimen per core. Specimens were heated in a MMTD80A furnace
306 (Magnetic Measurements) with 8-9 steps between 100 and 525°C. The direction was calculated

307 by principal component analysis. In order to correct the TRM direction for anisotropy effect (e.g.,
308 Veitch et al., 1984), the TRM tensor of each specimen was estimated by six heating at 500°C in a
309 laboratory field of 60 μ T applied successively along +z, -z, +x, -x, +y and -y axes of the specimen
310 (e.g., Chauvin et al., 2000). A last heating with the field along +z was finally performed to verify
311 the absence of changes in the ferromagnetic mineralogy during the anisotropy protocol. The
312 average inclination was calculated using McElhinny and McFadden (2000) statistics.

313 For dating, this average value was compared to the French secular variation curve recently
314 updated by Le Goff et al. (2020). First, the inclination was recalculated from Le Mans to the
315 reference location of the curve, Paris, using the assumption of a Geocentric Axial Dipole. The slight
316 latitudinal difference (0.9°) between the two cities did not induce a significant relocation error.
317 The dating process was performed on Chronomodel software (Lanos and Dufresne, 2019) with a
318 prior period between 0 and 800 CE.

319

320 **3.3 OSL**

321 **3.3.1 Some basics on OSL dating and types of studied samples**

322 The well-known principle of OSL dating has been presented in numerous review articles (Aitken,
323 1998; Wintle and Murray, 2006). Let's recall that the OSL of minerals originates in the absorption
324 of ionizing radiations coming from the natural radioactivity. In quantitative terms, the intensity
325 of OSL signals is a function of the radiation dose absorbed by the dated material, since its zeroing
326 process, the last light exposure or heating at more than 350°C. Like all paleo-dosimetric methods,
327 the OSL age of a sample is given by the ratio of the average archaeological dose measured on the
328 luminescent minerals selected for dating to the average annual dose rate to which these minerals
329 were exposed during the archaeological times.

330 Here, OSL studies focused on the remains of the urban fortification in the cellars of the city hall
331 and of the Gros-Pilier tower. Three types of materials were studied:

- 332 - Bricks: two samples taken from the gallery between the cellar and the lower room of the
333 Gros-Pilier tower, belonging to the outer facade of the fortification (Fig. S1b).
- 334 - Lime mortar: Four samples were taken in the urban fortification itself, two from the
335 foundation wall 11109 and two from the wall elevation 11108 (Fig. S1a-b). Four samples
336 were also taken in the Early Empire walls 11107 and 11120 and two complementary in
337 the wall 11121 of unknown period (Fig. S1c-d).
- 338 - Crushed *terracotta* mortar (*opus signinum*): this material consists in a lime mortar mixed
339 with sand and millimetric fragments of tiles and bricks. Two samples were taken from the
340 gallery close to the outer facade of the fortification by scrapping the surface of the masonry
341 (Fig. S1d).

342 In the case of bricks, OSL dates their last heating, i.e., their production as archaeomagnetic dating
343 does. In the case of lime mortars, the dated moment is the making of mortars, when lime and sand
344 are mixed. Due to the forced movement of mixing, quartz grains from the sand are only shortly
345 exposed to the ambient light when they reach the upper surface of the mixture and are thus
346 bleached partially. In such conditions, the statistical distribution of light exposure of grains
347 follows a decreasing exponential function (Guibert et al., 2017, 2020). In the case of crushed
348 *terracotta* mortars, the interpretation of results depends on the origin of the quartz grains, either
349 from the lime part or from the baked clay fragments. Apart from micro-dosimetric issues
350 (hereafter reported), OSL dates theoretically the construction when the time lapse between the
351 baked clay production and the making of mortar is insignificant. Otherwise, the consideration of
352 OSL signal of quartz grains from baked clay fragments provides a *terminus post quem* to the
353 construction.

354 All samples were collected under very low intensity orange LED light and tightly packed in opaque
355 boxes. The sample preparation is detailed in supplementary material.

356

357 **3.3.2 Determination of annual dose**

358 Concerning the determination of the dose rate components used in age calculation, different tools
359 were used according to the origin of irradiation. The sample matrix contribution of brick or
360 mortar was determined from low background gamma spectrometry measurements (Guibert et
361 al., 2009b) that provided the K, U and Th contents of the material being dated, and the state of
362 disequilibrium of the U-series. The K content was deduced from the single ^{40}K gamma line at
363 1460.8 keV. The Th content was determined by averaging all activities deduced from individual
364 lines of ^{228}Ac , ^{212}Pb , ^{208}Tl and then was converted into mass concentration. In the U series, we
365 distinguished different series of nuclides, that allowed us to evaluate the equilibrium state and
366 thus the possible past changes of dose rate due to changes in radiochemical composition (more
367 details for instance in Guibert et al., 2009b; Lahaye et al., 2012):

368 - the parent of the series given by ^{234}Th , $^{234\text{m}}\text{Pa}$ and ^{235}U emissions, the corresponding U content
369 being denoted $\text{U}(^{238}\text{U})$;

370 - immediate daughters of ^{226}Ra given by ^{214}Pb and ^{214}Bi , the equivalent U content being denoted
371 $\text{U}(^{226}\text{Ra})$, assuming equilibrium between ^{222}Rn and ^{226}Ra within the laboratory conditions;

372 - ^{210}Pb , the equivalent U concentration being denoted $\text{U}(^{210}\text{Pb})$.

373 The term “equivalent” illustrates the fact that the concentration of U was calculated from the
374 corresponding isotopes, assuming secular equilibrium with their very first parents. Calibration
375 uncertainties were around 1% for K, $\text{U}(^{238}\text{U})$, $\text{U}(^{226}\text{Ra})$, Th and 5% for $\text{U}(^{210}\text{Pb})$.

376 The elemental composition of samples was taken into account to correct intensities of gamma
377 lines for the self-attenuation that affects gamma emissions and particularly the low energy ones
378 like those of ^{210}Pb (46.5 keV) and ^{234}Th (63 keV). With these key-isotopes for the evaluation of the
379 equilibrium state of U-series, the self-attenuation is dependent on the composition in major
380 elements. In particular, this effect is important when comparing Ca rich samples, like mortars, to
381 low Ca reference samples, like the granite GS-N used as a standard to determine the precise K, U
382 and Th contents. All activities or mass contents of radio-elements were converted into the related
383 dose rates using the conversion factors published by Guérin et al. (2011), accounting for possible

384 disequilibria in the U series (U/Ra variations and ^{222}Rn flux in sample, monitored by ^{210}Pb ; see
385 Guibert et al., 2015 and Table S9 in supplementary material).

386 The environmental dose rate, which is the sum of gamma and cosmic dose rates, was measured at
387 the surface of every sampling location by on-site NaI:Tl gamma spectroscopy using a 1.5" \times 1.5"
388 probe (the dimensions of the probe being around 5 cm in diameter and 12 cm in length, we
389 avoided to drill large holes in the masonry) designed to measure counts up to 10 MeV. The good
390 separation of the gamma spectral region (0-3 MeV) and the cosmic one (3-10 MeV) allowed to
391 differentiate easily the two dose components. On-site $\text{Al}_2\text{O}_3\text{:C}$ dosimetry was also undertaken at a
392 10 cm depth inside the masonry at the precise location of the samples with pellets in a 12 mm
393 external diameter cylindrical container. This technique, less intrusive than gamma spectrometry,
394 integrates the whole environmental irradiation (gamma and cosmic rays). Finally, the
395 environmental dose rate of Le Mans samples was calculated as the mean value of on-site gamma
396 spectrometry and dosimetry, except for brick samples (BDX22220 and BDX22221) because only
397 NaI:Tl spectrometry data were available and for samples from the foundation wall 11109
398 (BDX22222 and BDX22223) for which the Al_2O_3 dosimetry results were preferred. In this latter
399 case, the presence of modern structures built close to the Late Roman Antiquity wall at this
400 location could have modified the "archaeological" gamma dose rate and we considered that the
401 dosimetry measurements inside the masonry were more significant than the spectrometry data
402 at the surface of the foundation wall.

403

404 **3.3.3 Determination of archaeological dose**

405 Standard OSL dating procedures were applied for dating bricks, following the usual single aliquot
406 regeneration (SAR) protocol on quartz inclusions (Murray and Wintle, 2000) according to the
407 classical multi-grain technique. In this study we used fine grains of quartz (3-11 μm) separated
408 from the powdered matrix using mechanical and chemical processes (Blain et al., 2007; see also
409 supplementary material). In addition to the usual determination of the archaeological dose by
410 beta laboratory irradiations, the alpha efficiency factor was measured using laboratory alpha

411 irradiations by a ^{241}Am source. We may note that the use of OSL is preferred to that of
412 thermoluminescence (TL), since both OSL and TL can date the last heating of quartz minerals. The
413 main reason is practical: the standard OSL protocol (SAR technique) is generally much more
414 precise than the TL one (“added dose technique and regeneration after heating”).

415 In the case of mortar samples, previous dating studies showed that it is necessary to examine the
416 bleaching state of individual grains (e.g., Goedicke, 2003, 2011; Panzeri, 2013), especially for
417 poorly bleached samples as we could expect here (Urbanová and Guibert 2017). A heterogeneous
418 bleaching of quartz grains in the mortar results in an age overestimation with the multigrain
419 technique. Therefore, all quartz grains, 200-250 μm in size, extracted from mortar samples (see
420 supplementary material for the preparation of samples) were exclusively studied by the single
421 grain technique, SG-OSL (Duller and Murray, 2000; Thomsen et al., 2005; Sim et al., 2013;
422 Medialdea et al., 2014; Urbanová and Guibert, 2017). The OSL signal was measured grain by grain
423 with a number of grains per sample between 2500 and 4000. Such high number of grains is
424 necessary to analyse the dose distribution and obtain the significant chronological information
425 carried by grains bleached during the mortar making. Specific tools are required to exploit the SG
426 data and we used in this study the Exposure Exponential Distribution (EED) model, developed
427 specifically for lime mortar dating (Guibert et al., 2017, 2020) (see supplementary material for
428 details).

429

430 **4. Results**

431 **4.1 Radiocarbon**

432 Detailed ^{14}C results are presented in Table S1 in supplementary material and intervals of
433 calibrated date at 95% of confidence in the Table 1. Dates from the same wall or structure are
434 generally in agreement. The case of the first state of the masonry under the arcade is an exception
435 with Lyon-15771(GrM) date on a small bone fragment is earlier than Lyon-15770(GrM) and Lyon-

436 15772(GrM) on charcoals. An older bone coming from the sand used in the mortar is the most
437 likely explanation of this slight time shift.

438 The earliest structure is the pit FS11648 in the excavation 11-600, dated between ~750 and ~400
439 BCE in the Early Iron Age plateau of the calibration curve. Dates in the 1st and 2nd centuries CE on
440 walls 11107 and 11120 confirm their attribution at the Early Empire period. The four dates
441 associated to the Late Roman Antiquity fortification place its construction between ~240 and
442 ~430 CE. Regarding the posterior structures, the two burials beneath the wall are not
443 contemporaneous, one being dated ~600 CE and the other one on the 10th century. The dated
444 walls around the collegiate are slightly later and concentrated between the second half of the 10th
445 and the 12th century.

446

447 **4.2 Archaeomagnetism**

448 The intensities of the natural remanent magnetization (NRM) vary between 0.08 and 42 A/m and
449 susceptibilities between 8×10^{-5} and 7×10^{-3} SI (Fig. S3 in supplementary material). Values are
450 more grouped for bricks of larger modulus from section C. Bricks of smaller modulus from
451 sections B and D have similar values that are well distributed all over the range of values. In
452 archaeological baked clays, the variation of the NRM intensity and of the susceptibility mainly
453 depends on the nature, size and number of ferromagnetic grains. These parameters are related to
454 the firing conditions (temperature and redox conditions) and to the composition of the initial clay.
455 The large variation of magnetic properties observed in the sections B and D might indicate the
456 presence of several productions. However, we think that it is rather due to the variation of firing
457 conditions inside the baking chamber of the kiln itself. Such variation is actually observed in
458 experimental archaeology (e.g., Hervé et al., 2019).

459 The dominance of unblocking temperatures between 400 and 550°C given by thermal
460 demagnetization suggest that the main carrier of the remanent magnetization is a titanium-poor
461 titanomagnetite. Almost all specimens (97/104) present a single stable component of

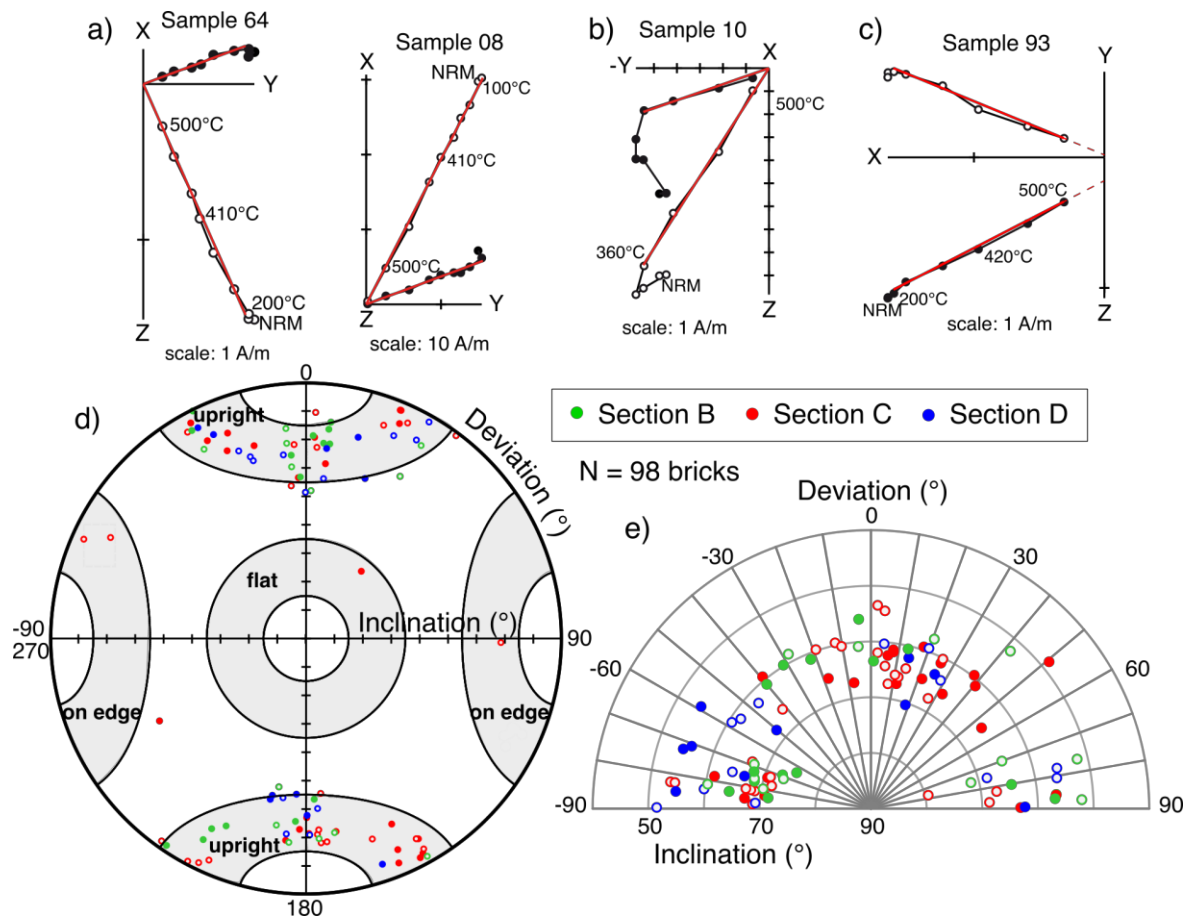
462 magnetization after removing a slight component below 100-280°C that is likely of viscous origin
463 (Fig. 4a). The low-temperature component is larger, up to 360-420°C, in four bricks (Fig. 4b). In
464 such case, one can also assume that the brick moved during the cooling in the kiln. Finally, for 3
465 bricks from section C, the TRM does not pass through the origin of the orthogonal plot (Fig. 4c).
466 The temperature in these bricks was not high enough to erase previous remanent magnetizations.
467 This behaviour might be explained by a location of the brick on the edges of the kiln. The TRM
468 direction could be determined on 102/104 bricks and the TRM tensor calculated for 98 specimens
469 (see Tab. S2 in supplementary material). The value of the stability check of the anisotropy protocol
470 (%alt in Tab S2) is up to 5.2% and below 2.5% for 85% of specimens, highlighting the reliability
471 of the correction for the TRM anisotropy effect. Anisotropy degrees vary from 4 to 36% with
472 similar values between sections. The TRM anisotropy correction results in directional changes by
473 a few degrees.

474 In the brick coordinates system (i.e., as in Fig. 3b), the three possible positions during the baking,
475 flat, upright or on edge, correspond to a range of deviation and inclination values on a
476 stereographic plot (Fig. 4d). 93/98 bricks appear baked in the upright position, providing a
477 further example that this position largely prevailed at the Roman period (Lanos, 1994). For other
478 bricks, all from the section C, one was baked in the flat position and four on edge.

479 After rotation in the baking position, similar TRM directions are obtained in the three sections,
480 both in inclination and deviation (Figure 4e). They are distributed in two clusters of
481 complementary deviations, one centred around +10° and the other one around -80° (bricks with
482 deviations around +80-90° belong to this second group). This configuration, very common at the
483 Roman period, corresponds to a checkerboard positioning of the bricks inside a rectangular
484 cooling chamber (Lanos, 1990, 1994).

485 The relative scatter between inclination values requires investigation before to calculate the
486 average inclination. The method assumed that drilling was done in the flattening plane of the
487 brick. But it was not easy to core really perpendicular to the side of the brick and all bricks are not

488 exactly horizontal in the masonry, which results in random experimental errors. One can also
 489 notice a tendency of higher inclination values in the group with deviations around -80° than in the
 490 one with deviations around $+10^\circ$. The effects of demagnetizing fields and of a dipping of the bricks
 491 could explain this difference (Lanos, 1994). The effect of demagnetizing fields, also named shape
 492 effect, occurs in flattened baked clays with a magnetization greater than 5–10 A/m (Lanos, 1987).
 493 For bricks baked upright, this effect results theoretically in an increase of the inclination (Lanos,
 494 1990). Here, no differences of TRM inclination with NRM intensity are observed (Fig. S4 in
 495 supplementary material). Therefore, the difference in inclination between the two groups of
 496 deviations appears rather due to a slight dip ($5\text{--}10^\circ$ for example) of the bricks, a positioning that
 497 improves the stability of the loading in the kiln.



498
 499 Figure 4: Archaeomagnetic directional results. (a-c) Representative orthogonal plots with open
 500 (solid) circles being the projections upon vertical (horizontal plane). The red line shows the
 501 direction of the TRM component determined by principal component analysis. (b) Stereographic

502 plot of TRM directions in the coordinate system of the brick after correction for TRM anisotropy.
503 Solid and open circles correspond to positive and negative inclinations respectively. Grey shaded
504 areas highlight range of values corresponding to the three possible positions in this coordinate
505 system. (c) Stereographic plot of the directions after rotation in the baking position providing an
506 inclination consistent with the secular variation ($\sim 55\text{-}75^\circ$ in France).

507

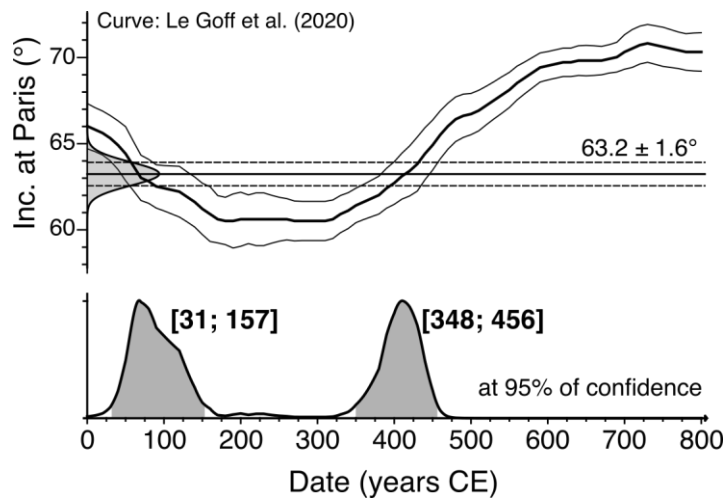
508 Measurements on modern bricks and numerical simulations show that bricks with a deviation
509 around 0° , i.e. with their flattening plane closely parallel to the surrounding geomagnetic field
510 during the baking, preserved the true inclination value, while it is modified in bricks with
511 deviation around 90° (Lanos, 1994). We consider thus that only the bricks with a deviation of
512 $+10\pm 30^\circ$ are relevant for the calculation of the average inclination. Among these 35 bricks, 5 come
513 from the section B, 24 from the section C and 6 from the section D. The number of bricks per
514 section is too low to be able to estimate a mean value for each of them. As inclinations are not
515 significantly different between the three sections, the average value used for dating was calculated
516 using the 35 selected bricks.

517

518 The average value of 62.5° has a radius of the 95% confidence circle (α_{95}) equal to 1.6° and a
519 precision parameter (k) of 226. The comparison of the value relocated to Paris (63.2°) with the
520 French secular variation curve (Le Goff et al., 2020) provides two intervals of date at 95% of
521 confidence, [31; 157] and [348; 456] CE (Fig. 5). As the archaeological context favours the
522 hypothesis of a production specifically for the construction of the section 11-300,
523 archaeomagnetic dating indicates a baking of bricks more likely in the second interval between
524 the middle of the 4th and the middle of the 5th century for. Nevertheless, archaeomagnetism alone
525 cannot formally exclude that bricks were produced at the Early Empire period and reused from
526 former buildings.

527

528



529

530 Figure 5: Archaeomagnetic dating of the bricks from section 11-300 of the Late Roman Antiquity
531 wall. The comparison of the average inclination relocated to Paris provides a probability density
532 function, on which are defined two intervals of date at 95% of confidence.

533

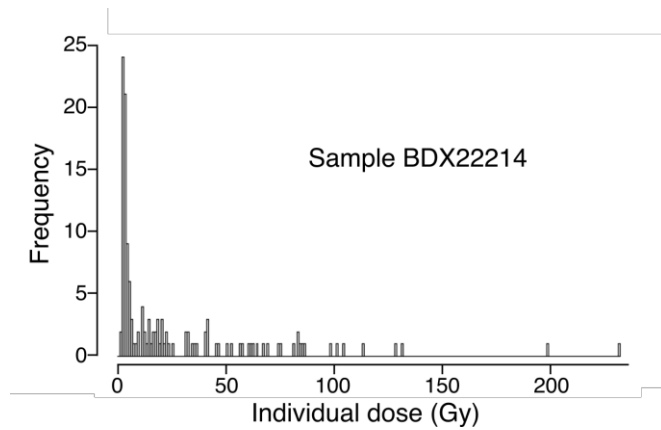
534

535 4.3 OSL

536 4.3.1 Determination of archaeological doses by OSL

537 SG OSL results for mortars are given in Table S3. The dose of individual grains ranged from 1 to
538 more than 500 Gray (Gy) in lime mortar samples (Fig. 6). This large scatter, which is not abnormal
539 with this type of sample, highlights a heterogeneous bleaching of the quartz grains. The
540 concentration of grains in the low dose region corresponds to the best bleached grains.
541 Conversely, the large tail towards high doses corresponds to unbleached or poorly bleached
542 grains whose OSL shows the presence of residual “geological” signal characterizing the initial OSL
543 state of the sedimentary sand used by the ancient masons. Only the mean archaeological dose
544 corrected for these residuals is relevant to estimate the mean dose acquired by the studied quartz
545 grains since the mortar making (see Guibert et al., 2020 for details).

546



547

548 Figure 6: Histogram of individual equivalent doses of quartz grains extracted from a
 549 representative lime mortar sample (BDX22214).

550

551 The proportion of grains with a sufficiently intense OSL signal, i.e., usable for dose determination,
 552 is low, between 0.5 and 3.5 %, in lime mortars, while it reaches ~25-30% in crushed *terracotta*
 553 mortars (Tab. S5). In this type of mortar, as heating enhances the sensitivity to OSL, quartz grains
 554 from the baked clay fragments likely represents the most important part, ~90%, of grains with a
 555 measurable OSL signal. The higher representation of the baked clay fragments also results in
 556 kappa factors around 200 much higher than those of lime mortars. The low values of kappa in
 557 pure lime mortars, ranging between 2.6 and 7.8, indicate a relatively low level of exposure,
 558 corresponding approximately to a 5-15 seconds time of “full sun equivalent” mean exposure
 559 (Godfrey-Smith et al., 1988).

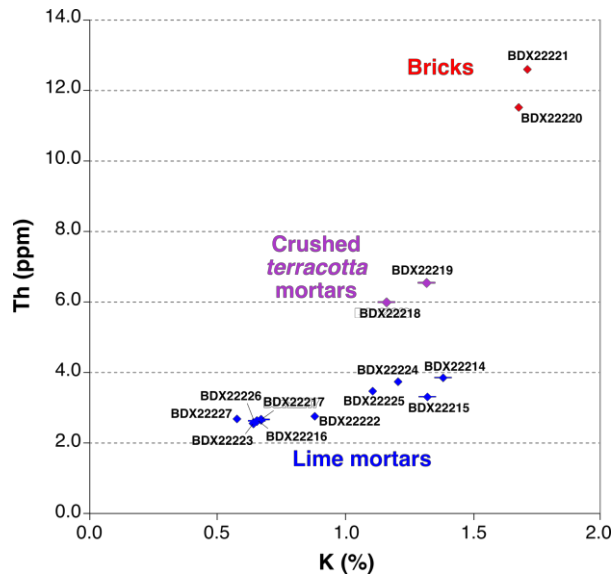
560 Finally, archaeological doses from standard OSL experiments on bricks are given in Tables S6 and
 561 S7. Bricks generally provide a more precise estimation than mortars, because the deposit of
 562 thousands of fine grains on discs results in a better reproducibility of OSL emissions compared to
 563 the SG-OSL results with a low number of measurable individual grains.

564

565 **4.3.2 Determination of annual doses**

566 The Table S8 reports the natural (i.e., as sampled) moisture content and radiochemical
 567 composition of the dried samples. The K-Th diagram illustrates important differences of internal
 568 radioactivity between bricks and mortars (Fig. 7). The crushed *terracotta* mortars exhibit a

569 radioactivity between bricks and pure lime mortars indicating a composition typically ca. 70%
 570 lime mortar and 30% crushed ceramic. These observations will help us to interpret the dating
 571 results on terracotta mortars in the next section.



572
 573 Figure 7: K-Th concentrations in OSL samples illustrating differences in internal radioactivity
 574 according to their nature.

575
 576 A difference between uranium and radium activities can be observed in some samples (Tab. S8).
 577 This is related to the long-life elements that are potentially mobile due to weathering processes
 578 (Guibert et al. 2009b). A slight disequilibrium is observed in bricks and mortars, $U^{(238)U}$ being
 579 lower than $U^{(226)Ra}$, except for samples from the foundations of the Late Roman Antiquity wall
 580 (wall 11109) and from the Early Empire wall 11120. At the present stage of study, we cannot
 581 identify which element, U or Ra or even both, was affected by a variation of concentration in the
 582 past. The radon mobility (^{222}Rn), which is also a meaningful concern in luminescence dating, can
 583 be evaluated by comparing $U^{(226)Ra}$ with $U^{(210)Pb}$. As radiochemical analyses were performed
 584 shortly after sampling (i.e., some months), the activity of ^{210}Pb reflects the one of radon (^{222}Rn
 585 from ^{238}U series) during the last 30 years and thus characterizes the budget of radon within the
 586 materials under the archaeological conditions (before sampling and laboratory storage). In all
 587 samples, the absence of significant differences between ^{226}Ra and ^{210}Pb activities highlights no

588 transport of radon. Radium was likely a stable element at this site with no enrichment on grain
589 surfaces by precipitation from ground water. Otherwise, we would have observed a
590 disequilibrium with ^{210}Pb (less ^{210}Pb than ^{226}Ra), as the ^{222}Rn formed by decay of ^{226}Ra could not
591 have been maintained trapped inside minerals. According to this result, we consider that the
592 disequilibrium between ^{238}U and ^{226}Ra in almost all samples mainly originates in a movement of
593 uranium. The calculation of annual dose considers this disequilibrium, assuming it was constant
594 through time.

595 The Table S10 reports the different components of annual dose rates. Attenuation factors of alpha
596 and beta dose rates for the 200-250 μm quartz grains in mortars were deduced from Brennan et
597 al. (1991) and Mejdahl (1979) data. For these samples, the alpha efficiency factor was defined
598 with a standard value of $k = 0.05 \pm 0.02$ (Bailiff 2007, Guibert et al., 2009a), while the k-factor was
599 directly measured in the case of bricks studied using the quartz fine grain technique.

600

601 **4.3.3 Summary of OSL results**

602 The Table 2 reports archaeological doses, annual doses, OSL ages and dates, as well as their
603 statistical, systematic and total uncertainties. The total uncertainty is the quadratic sum of two
604 errors, the statistical one and the systematic one. The systematic uncertainty is related to the
605 calibration of measurements systems. For instance, the beta source calibration error for a given
606 OSL machine is a common uncertainty for all samples measured with that equipment.

607 The statistical uncertainty refers to the precision and the reproducibility of measurements within
608 a sample. The lowest values are observed on bricks mainly because the measurements with the
609 standard multigrain technique on quartz fine grains are very reproducible and because their k-
610 factor of the alpha efficiency is precisely measured. In mortar samples, the k-factor is a standard
611 value associated with a high uncertainty, although this disadvantage of SG-OSL technique is
612 minimized by the fact that the alpha annual dose is a very minor component because the
613 individual grains are around 10 times larger than the range of alpha particles. Apart these intrinsic
614 limitations, the higher statistical uncertainty of SG-OSL dates is also related to the dispersion of

615 the dose distribution and, further in our study, to the number of grains that are sufficiently bright
616 for dose measurement, the greater the number, the lower the statistical uncertainty.

617 The Late Roman Antiquity wall concentrates the most OSL results with 8 dates obtained on bricks,
618 lime mortars, crushed *terracotta* mortars from the wall itself (wall 11108) and on lime mortars
619 from its foundation (wall 11109). The SG-OSL dates (Tab. 2 and Fig. 8) on lime mortars are in
620 agreement within uncertainties between the walls 11108 and 11109 and centered on the Late
621 Roman Antiquity period (4-5th centuries). No significant gap is also observed with the results on
622 the two bricks. It suggests that bricks were produced for the construction and not reused from a
623 former monument but this hypothesis must be investigated with the whole set of dating results
624 (see section 5.1).

625 The two samples of crushed *terracotta* mortars provide earlier dates with an average in the
626 second century BCE. This apparent inconsistency with the archaeological context has a physical
627 explanation related to the different contributions of the lime mortar and baked clay fragments to
628 the archaeological and annual doses. The gamma spectrometry analysis indicates that these
629 samples are constituted by ca. 70% of pure lime and 30% of baked clay (Fig. 7) and the two
630 components take part to the annual dose in these proportions. However, in reason of their high
631 sensitivity (30% of grains with a sufficiently intense OSL signals, instead of 0.5-3.5% for unbaked
632 grains), grains from baked clay fragments represent around 90% of the accepted grains used for
633 the archaeological dose measurement. As a matter of fact, the provenance of OSL
634 grains does not respect the proportion of materials (lime and baked clay). In addition, the
635 dimensions of the *terracotta* fragments (a few millimeters) imply that the beta dose-rate of the
636 dated grains originates essentially from the baked clay, much more radioactive than the major
637 component of the sample, the lime cement. As a result, the annual doses deduced from analyses
638 of the entire sample are underestimated and the corresponding ages are overestimated. However,
639 we can consider the OSL dates as *termini post quem* for the construction of the late Roman
640 Antiquity wall. Our results highlight that further research on OSL dating of crushed *terracotta*
641 mortars is required. Being able to separate the baked clay fragments from the rest of the mortar

642 would allow to better determine archaeological and annual doses, as well as to take into account
 643 the probable use of “old” *terracotta*. Moreover, the high heterogeneity of the beta radiation field
 644 within sample needs to be considered in the annual dose evaluation, by using for instance the
 645 DOSIVOX facilities with complementary local elementary analysis of K, U and Th (Martin et al.,
 646 2015).

647

648 Table 2: SG-OSL and OSL results. Location of the sample; laboratory name of the sample; type of
 649 material; archaeological dose; annual dose; OSL age in years before the year of experiments
 650 (2019); systematic uncertainty; statistical uncertainty; total uncertainty; date with 1σ standard
 651 deviation. Uncertainties are expressed in standard deviation. Archaeological and annual doses
 652 are rounded to the second decimal.

Context	Sample	Material	Arch. dose (Gy)	Annual dose (mGy/yr)	Age (yrs)	Syst. unc. (yrs)	Stat. unc. (yrs)	Tot. unc. (yrs)	Date $\pm 1\sigma$ (yrs CE)
Late Roman Antiquity wall, gallery between the cellar of the city hall and the Gros-Pilier tower room, wall 11108									
	BDX 22216	lime mortar	1.56 \pm 0.14	1.01 \pm 0.06	1553	80	152	173	466 \pm 173
	BDX 22217	lime mortar	1.49 \pm 0.08	0.96 \pm 0.05	1553	77	85	128	466 \pm 128
	BDX 22220	brick	5.69 \pm 0.26	3.23 \pm 0.14	1762	86	50	107	257 \pm 107
	BDX 22221	brick	5.35 \pm 0.22	3.30 \pm 0.15	1621	79	28	92	398 \pm 92
	BDX 22218	crushed <i>terracotta</i> mortar	3.15 \pm 0.02	1.47 \pm 0.10	2139	120	106	162	TPQ :-120 \pm 162
	BDX 22219	crushed <i>terracotta</i> mortar	3.45 \pm 0.02	1.56 \pm 0.11	2207	131	105	170	TPQ : -188 \pm 170
Late Roman Antiquity wall, Gros-Pilier tower room, foundation wall 11109									
	BDX 22222	lime mortar	1.65 \pm 0.12	1.00 \pm 0.06	1648	99	127	162	371 \pm 162
	BDX 22223	lime mortar	1.28 \pm 0.21	0.84 \pm 0.09	1526	91	286	301	493 \pm 301
Early Empire structure, cellar of the city hall, wall 11120									
	BDX 22224	lime mortar	2.49 \pm 0.17	1.40 \pm 0.07	1780	99	127	161	239 \pm 161
	BDX 22225	lime mortar	2.44 \pm 0.10	1.27 \pm 0.07	1920	107	96	145	99 \pm 145
Early Empire structure, cellar of the city hall, wall 11107									
	BDX 22214	lime mortar	2.68 \pm 0.08	1.49 \pm 0.07	1800	92	63	114	219 \pm 114
	BDX 22215	lime mortar	2.68 \pm 0.18	1.48 \pm 0.06	1811	92	124	155	208 \pm 155
Undetermined period, cellar of the city hall, wall 11121									
	BDX 22226	lime mortar	2.55 \pm 0.07	0.92 \pm 0.05	2629	110	134	175	-610 \pm 175
653	BDX 22227	lime mortar	1.78 \pm 0.12	0.89 \pm 0.04	1973	101	147	179	46 \pm 179

654

655 Regarding the former constructions, the OSL dates of the walls 11107 and 11120 are consistent
 656 with each other and with stratigraphy. Conversely, the two OSL dates of the wall 11121, possibly
 657 medieval, are problematic because of their large inconsistency and of their high ages. We have no

658 clear interpretation about such results. A hypothesis could be the fact that the mortar was
659 prepared in very low light exposure conditions, for instance inside a pre-existing building (see
660 Guibert et al., 2020 for a detailed discussion on this possible limitation of mortar dating by OSL).
661 In such case, quartz grains could not be bleached at the mortar making and the OSL dates might
662 be rather those of the sediment deposition (the sediment which was mixed with lime).
663 Unfortunately, no charcoal could be found in the mortar of the wall 11121 in order to verify this
664 hypothesis.

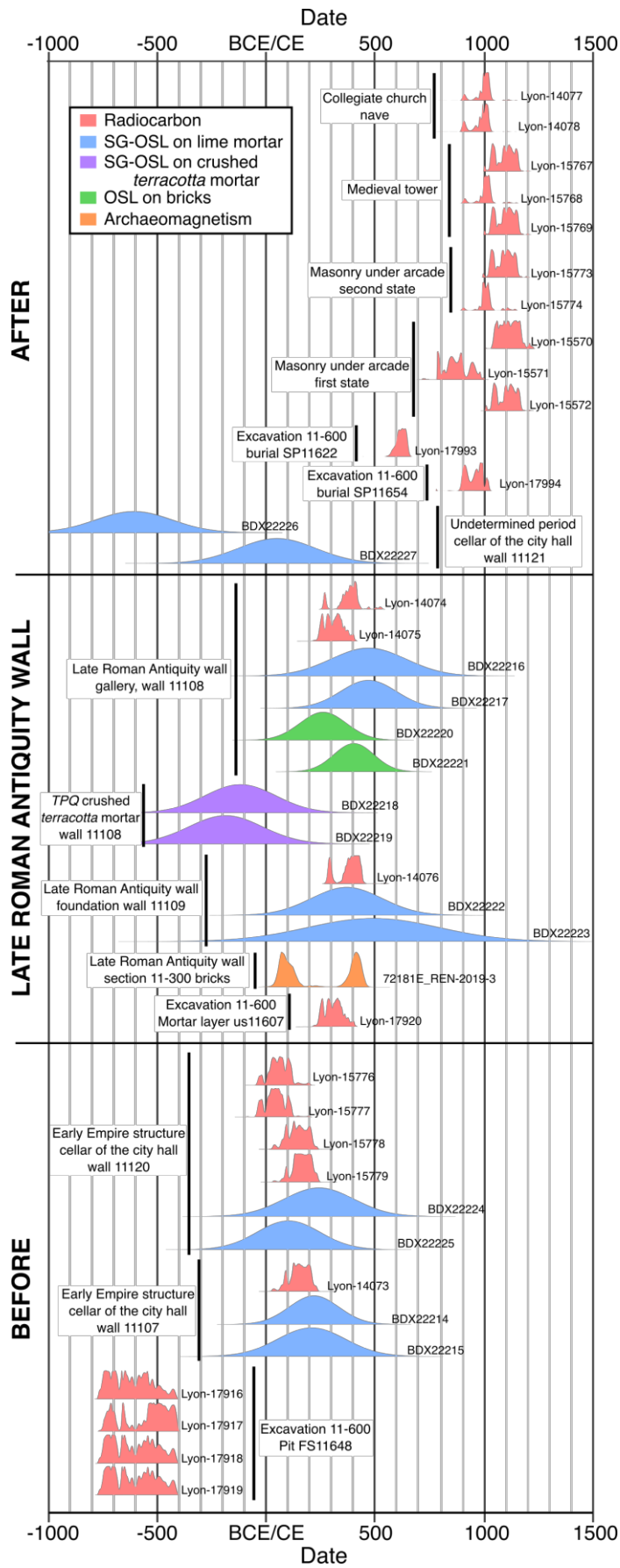
665

666 **5. Discussion**

667 **5.1 Synthesis of chronological data**

668 The results of all methods are plotted in Figure 8. Except the two burials, all structures have at
669 least two dates with a maximum of 13 for the Late Roman Antiquity wall (including the two on
670 crushed *terracotta* mortar). In the case of bricks, the two OSL dates confirm that the youngest date
671 interval given by archaeomagnetism at the Roman period, i.e. [348; 456] CE, should be preferred.
672 Overall, methods give consistent results for the Late Roman Antiquity wall, the Early Empire walls
673 and medieval buildings. The wall 11121 in the cellar of the city hall constitutes the sole exception
674 with a large disagreement between one OSL date at the turn of the Christian era and another one
675 in the Early Iron Age, a period at which masonry was unknown in Northern Gaul. Our results
676 cannot help to precise the date of construction, possibly medieval, of this wall.

677 All other chronological data were integrated in a hierarchical Bayesian model (Figure S5). We use
678 Chronomodel 2.0 software (Lanos and Dufresne, 2019) that is based on the concept of Event date
679 (Lanos & Philippe, 2018). An Event groups data coming from the same structure and therefore
680 supposed contemporaneous. In addition to the experimental uncertainties, the Event model
681 introduces an individual error on each data to take into account the possibility of a systematic
682 error on the date. The relationships of anteriority or posteriority provided by the stratigraphy
683 constitute prior information that helps to constrain the date of each event.



684

685 Figure 8: Summary of radiocarbon, SG-OSL, OSL and archaeomagnetic dates.

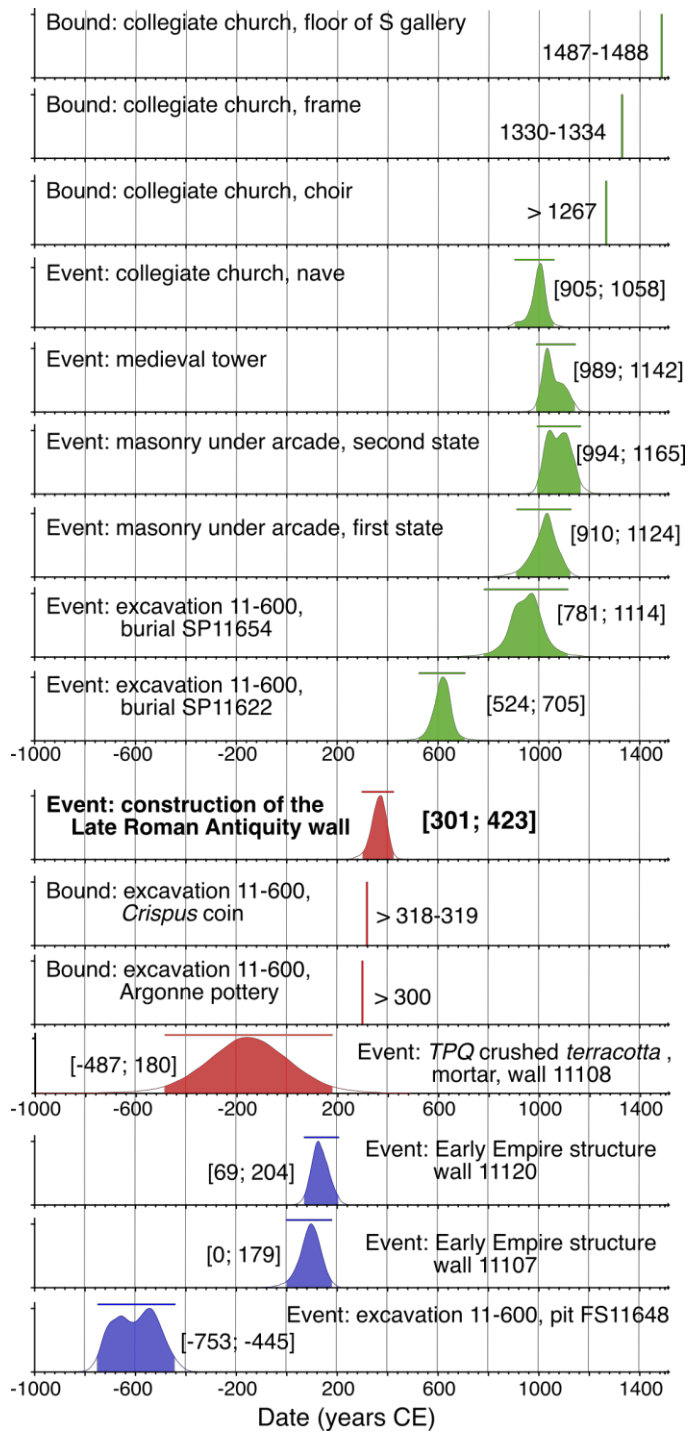
686

687 The main event of the model is related to the construction of the Late Roman Antiquity wall. We
688 decided to assign it all the radiocarbon, archaeomagnetic, OSL and SG-OSL dates on lime mortars
689 and bricks from the wall itself (wall 11108) and its foundations (wall 11109) (Figure S5). This
690 choice considers that studied bricks were not reused from a former monument but produced
691 specifically for the Late Roman Antiquity wall. In the sector 11, this hypothesis is supported by
692 the homogeneity of brick in sampled brick courses and not denied by the consistent results,
693 regarding experimental errors, on bricks and lime mortars. It is worth pointing out that this choice
694 could be not valid for another sector of the wall. Conversely, the two SG-OSL data on crushed
695 *terracotta* mortar are included in another event, because an intrinsic physical reason ascertain
696 that they do not date the construction but provide a *Terminus Post Quem*.

697 Besides physical dates, the model also integrates the dates of Crispus coin and Argonne *sigillata*
698 deposited shortly after the construction (see section 2.1), as well as those given by historical
699 sources and dendrochronology at the medieval period. These data, which constitute *Termini Post*
700 *Quem* or *Termini Ante Quem*, are not entered as events in Chronomodel but as bounds that are
701 defined as events with a known date.

702 The Bayesian model was performed with a prior study period between 1000 BCE and 1500 CE.
703 The Markov chain Monte Carlo (MCMC) process included 3 chains, each one with 100 k iterations
704 in the acquisition phase. Results of the model are presented in Figure 9 and discussed in the next
705 sections.

706



707

708 Figure 9: Results of Bayesian chronological modelling using Chronomodel 2.0 software with the
 709 probability density function (pdf) of each event. The line above the pdf indicates the highest
 710 posterior density intervals at 95% of confidence. The events and bounds related to the
 711 construction of the Late Antiquity Roman wall are in red, those before the construction in blue
 712 and those posterior to the construction in green.

713

714

715 **5.2 Construction of the Late Roman Antiquity urban fortification**

716 The Bayesian Event of the construction of the Late Roman Antiquity wall in the sector 11 presents
717 a monomodal probability density function providing an interval of date between 301 and 423 CE
718 at 95% of confidence. It is worth pointing out that this result does not depend on our choice to
719 include dates on lime mortars (radiocarbon and SG-OSL) and bricks (OSL and archaeomagnetism)
720 in the same event in the Bayesian model. Another model separating the two materials in two
721 different events give a very similar interval of date between 295 and 428 CE at 95% of confidence
722 for the building of the fortification.

723 The new dating invalidates the previous estimation of 280 ± 15 CE from Goulpeau (1985) given
724 by an archaeomagnetic study on a set of bricks from another sector of the wall in the western part
725 along the Sarthe River. Note that the unreliability of this previous date does not come from not
726 the result itself but from the dating process in use at this time. Using the statistically robust
727 modern Bayesian method, the average inclination ($63.5 \pm 3.0^\circ$, $n=28$ specimens, $k=74$) results in
728 an interval of [301; 551] at 95% of confidence, close to the values of the present new study.
729 Besides being more precise, our new date between 301 and 423 is also more reliable because it is
730 based on several methods and materials. The result is consistent with the *Termini Post Quem* of
731 the Crispus *nummus* coin and of the Chenet 320 cup in Argonne *sigillata* found in a layer shortly
732 deposited after the construction through excavation 11-600.

733 The new date between the beginning of the 4th century and the beginning of the 5th century clearly
734 excludes that the wall, at least in the studied sector, was built in the last third of the 3rd century as
735 previously thought. Therefore, the construction of the Late Roman Antiquity walls likely occurred
736 in a period characterized by a restoration of the imperial order and of economy, perhaps around
737 320-360 either under Constantine or one of his immediate successors. However, caution is needed
738 on this point because all new dates come from only one sector of the city, while the construction
739 of the overall urban fortification could last several decades.

740 Besides its chronological aspect, our study contributes to the knowledge of the construction work.
741 In the sector of the Gros-Pilier tower, the dates obtained on the walls 11107 and 11120 ([0; 179]
742 and [69; 204] CE at 95% of confidence respectively) show that the Late Roman Antiquity wall
743 encompassed Early Empire walls. Moreover, if the large stone blocks from the foundation clearly
744 came from former monuments of this period, the absence of a significant time shift between dates
745 on bricks and lime mortars shows that, at least in this sector of the city, bricks were not reused
746 from Early Empire constructions built before the mid 3rd century. Even though the dating
747 uncertainties do not make impossible that they came from structures shortly built before, their
748 size homogeneity within a section and the absence of fragmentation in the wall 11-300 strongly
749 suggest that bricks were rather produced for the construction of the Late Roman Antiquity walls.

750 At the beginning of our study, the question of a reuse arose especially for the bricks of large
751 modulus, as the size of bricks tended to decrease throughout the Roman period in Gaul (e.g.,
752 Nauleau, 2013). In the section 11-300, similar average inclination values are obtained for the
753 bricks, having a $10\pm 30^\circ$ deviation, of small ($61.8\pm 2.7^\circ$, n=11 bricks) and large ($62.8\pm 1.9^\circ$, n=24
754 bricks) modulus. Therefore, the presence of two moduli likely corresponds to a procurement from
755 at least two different workshops rather than by the reuse of one set of brick. Such multiple
756 procurement is not surprising regarding the huge quantity (around 400,000) of bricks required
757 for the construction of the urban walls (Nauleau, 2019).

758 Finally, the sector 11-300 divided in four different sections highlights the progressive
759 construction of the fortification. The duration between the edification of each section was likely
760 very short, from a few weeks to a few years, and the precision of dating techniques cannot be
761 sufficient to investigate it.

762

763 **5.3 Evolution of the sector 11 at the Medieval period**

764 Our dating results clarify the chronology of the evolution of the Late Roman Antiquity walls in the
765 sector 11 during the medieval period. First, recent archaeological excavations, as in the 11-600

766 area, highlight the presence of burials against the base of the wall (Bouillet et al., 2022). The two
767 radiocarbon dates circa 600 CE for the burial SP11622 ([574; 651] Cal yrs CE at 95% of
768 confidence) and in the 10th century for the burial SP11654 ([891; 996] and [1003; 1020] Cal yrs
769 CE at 95% of confidence) show that this practice lasted over all the Early Middle Age.

770 At the same period, important civil buildings, which became later the Counts of Maine residence
771 at the present location of the city hall and collegiate church Saint-Pierre-de-la-Cour, were
772 probably built within the city walls against the fortification. However, the architecture of the walls
773 themselves does not seem significantly modified in this sector before the 10-11th centuries and
774 the construction of the first collegiate church.

775

776 **6. Conclusion**

777 Based on 40 new ¹⁴C, OSL (quartz fine grain technique), SG-OSL and archaeomagnetic dates in a
778 limited well-preserved sector, our study reassesses the date of construction of the Late Roman
779 Antiquity walls and precises the evolution of this area from the protohistoric to the medieval
780 periods. All results were integrated in a Bayesian chronological model together with stratigraphy
781 and temporal constraints provided by archaeological artefacts and historical sources. The
782 chronological model dates the construction of the Late Roman Antiquity walls between 301 and
783 423 CE at 95% of confidence. This result unambiguously excludes that it occurred during the
784 crises of the 3rd century, as previously thought, but rather in the stable political context of the 4th
785 century.

786 Besides chronological aspects, crossing dating methods give information on the construction
787 work of the Late Roman Antiquity walls. The consistency of archaeomagnetic and OSL dates on
788 bricks with the ¹⁴C and SG-OSL dates on lime mortars shows that bricks were not reused from
789 former building, at least in this sector of the walls. They were produced for the construction of the
790 walls with the presence of several types of bricks likely reflecting a supply from at least two local
791 workshops.

792 From a methodological point of view, this study constitutes a new example of the applicability of
793 SG-OSL to date lime mortars. Conversely, further methodological research is required for crushed
794 *terracotta* mortars. For physical reasons, their mixed composition of lime mortar and baked clay
795 fragments can only provide a *Terminus Post Quem* to the construction.
796 Finally, our study shows the importance of crossing dating methods in a close interdisciplinary
797 collaboration to get the most relevant information. The use of a single dating method (OSL or
798 radiocarbon or archaeomagnetism) would not have allowed such robust chronology and
799 interpretations of the building of the Late Roman Antiquity walls, because each method dates
800 different events (manufacture of bricks by archaeomagnetism and OSL, growth of vegetal
801 elements corresponding to the charcoals embedded in mortar by ^{14}C , making of mortar by SG-
802 OSL). Crossing all these chronological events is then much more suitable for the knowledge of the
803 construction. In addition, typochronological methods can admittedly be more precise but
804 artefacts clearly associated to the building are very rare, or even exceptional (i.e., accidental?), in
805 such archaeological contexts. The *Crispus* coin and the Argonne ceramic found in the excavation
806 11-600 were in fact unexpected at the starting of the study. The good results of our methodology
807 encourage its application in other Late Roman Antiquity fortifications. Revisiting their chronology
808 would help to better understand the historical context of the development of these monumental
809 constructions.

810

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829

830

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1056 **Figure captions**

1057 Figure 1: (a) General plan of the Late Roman Antiquity urban fortification at Le Mans. (b) Plan of
1058 the sector 11 highlighting sampled walls and structures. (c) View of the sector 11 from South-East
1059 i.e., from outside the Roman walls. (d) Drawing of the section 11-300. The red arrows indicate the
1060 lowest brick course sampled for the archaeomagnetic study. (From Meunier and Monteil, 2019,
1061 2020; CAD: H. Meunier)

1062

1063 Figure 2: Simplified stratigraphic diagram of studied contexts with the number of obtained dates.
1064 The diagram reproduces the formalism of Chronomodel software (Lanos and Dufresne, 2019).
1065 Rectangular boxes correspond to dated events, while circular boxes indicate *Termini Ante Quem*
1066 and *Post Quem* (called bounds in Chronomodel). The structures related to the construction of the
1067 Late Antiquity Roman wall are in red, those before the construction in blue and those posterior to
1068 the construction in green.

1069

1070 Figure 3: (a) In the hypothesis of a baking of the brick on one face, only one of the three possible
1071 positions provides an inclination value in agreement with the secular variation in France over the
1072 last millennia (from Lanos, 1994). (b) Orientation of the archaeomagnetic specimens within the
1073 brick and directional components of the TRM in this coordinate system.

1074

1075 Figure 4: Archaeomagnetic directional results. (a-c) Representative orthogonal plots with open
1076 (solid) circles being the projections upon vertical (horizontal plane). The red line shows the
1077 direction of the TRM component determined by principal component analysis. (b) Stereographic
1078 plot of TRM directions in the coordinate system of the brick after correction for TRM anisotropy.
1079 Solid and open circles correspond to positive and negative inclinations respectively. Grey shaded
1080 areas highlight range of values corresponding to the three possible positions in this coordinate

1081 system. (c) Stereographic plot of the directions after rotation in the baking position providing an
1082 inclination consistent with the secular variation ($\sim 55\text{-}75^\circ$ in France).

1083

1084 Figure 5: Archaeomagnetic dating of the bricks from section 11-300 of the Late Roman Antiquity
1085 wall. The comparison of the average inclination relocated to Paris provides a probability density
1086 function, on which are defined two intervals of date at 95% of confidence.

1087

1088 Figure 6: Histogram of individual equivalent doses of quartz grains extracted from a
1089 representative lime mortar sample (BDX22214).

1090

1091 Figure 7: K-Th concentrations in OSL samples illustrating differences in internal radioactivity
1092 according to their nature.

1093

1094 Figure 8: Summary of radiocarbon, SG-OSL, OSL and archaeomagnetic dates.

1095

1096 Figure 9: Results of Bayesian chronological modelling using Chronomodel 2.0 software with the
1097 probability density function (pdf) of each event. The line above the pdf indicates the highest
1098 posterior density intervals at 95% of confidence. The events and bounds related to the
1099 construction of the Late Antiquity Roman wall are in red, those before the construction in blue
1100 and those posterior to the construction in green.

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1103 **Table captions**

1104 Table 1: Summary of chronological data. Context: location of the sample; Dating method; Dated
1105 material or artefact; Laboratory number of the sample for physical dating techniques; Results
1106 before calibration for physical dating techniques: uncalibrated age with 1σ standard deviation for

1107 ^{14}C , age in years before year of measurement with 1σ standard deviation for OSL, average
1108 inclination with radius of the 95% confidence circle (α_{95}), precision parameter (k) and number of
1109 bricks for archaeomagnetism; Date intervals.

1110

1111 Table 2: SG-OSL and OSL results. Location of the sample; laboratory name of the sample; type of
1112 material; archaeological dose; annual dose; OSL age in years before the year of experiments
1113 (2019); systematic uncertainty; statistical uncertainty; total uncertainty; date with 1σ standard
1114 deviation. Uncertainties are expressed in standard deviation. Archaeological and annual doses
1115 are rounded to the second decimal.

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