New archeointensity data from French Early Medieval pottery production (6th–10th century AD). Tracing 1500 years of geomagnetic field intensity variations in Western Europe

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Abstract

Nineteen new archeointensity results were obtained from the analysis of groups of French pottery fragments dated to the Early Middle Ages (6th to 10th centuries AD). They are from several medieval ceramic production sites, excavated mainly in Saran (Central France), and their precise dating was established based on typo-chronological characteristics. Intensity measurements were performed using the Triaxe protocol, which takes into account the effects on the intensity determinations of both thermoremanent magnetization anisotropy and cooling rate. Intensity analyses were also carried out on modern pottery produced at Saran during an experimental firing. The results show very good agreement with the geomagnetic field intensity directly measured inside and around the kiln, thus reasserting the reliability of the Triaxe protocol and the relevance of the quality criteria used. They further demonstrate the potential of the Saran pottery production for archeomagnetism. The new archeointensity results allow a precise and coherent description of the geomagnetic field intensity variations in Western Europe during the Early Medieval period, which was until now poorly documented. They show a significant increase in intensity during the 6th century AD, high intensity values from the 7th to the 9th century, with a minimum of small amplitude at the transition between the 7th and the 8th centuries and finally an important decrease until the beginning of the 11th century. Together with published intensity results available within a radius of 700 km around Paris, the new data were used to compute a master curve of the Western European geomagnetic intensity variations over the past 1500 years. This curve clearly exhibits five intensity maxima: at the transition between the 6th and 7th century AD, at the middle of the 9th century, during the 12th century, in the second part of the 14th century and at the very beginning of the 17th century AD. Some of these peaks are smoothed, or nearly absent when the selection of the data is extended to a 1250 km radius around Paris. The apparent regularity in the occurrence of intensity maxima, with a recurrence of ~250 years, is particularly intriguing and might reflect a new characteristic of the secular variation, at least in Western Europe. It clearly requires further investigation and in particular the acquisition of new data from older periods.

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1. Introduction

The Early Middle Ages in Western Europe spanned from the end of the 5th century to the beginning of the 11th century AD (e.g. Devroey, 2003; Davis, 2005). The perception of this period, often called the “Dark Ages”, has largely been re-evaluated in France over the past 20 years thanks to rescue archaeology. Numerous archeological excavations conducted during the re-development within towns and in the countryside have enabled a better understanding of the medieval habitat and of everyday life. This new information has revealed a less abrupt transition period after the fall of the Roman Empire (e.g. Catteddu, 2009). Furthermore, these
excavations have offered unique opportunities for studying the geomagnetic secular variation during this time interval. In particular, a large set of domestic kilns was sampled for archeomagnetic directional analyses in the Île-de-France region, near Paris (Warmé, 2009) and the new results aim to contribute to the refinement of the French directional variation curve during the Middle Ages. The discovery of pottery workshops, ranging from small units to large production centers, also provided material for archeomagnetic directional and/or intensity studies.

The need for new archeointensity results from the Early Middle Ages has long been recognized (e.g. Chauvin et al., 2000; Genevey and Gallet, 2002). Despite recent and significant improvements (Donadini et al., 2008, 2012; Gallet et al., 2009; Tema et al., 2009; Gómez-Paccard et al., 2012), this period remains poorly documented, which penalizes the construction of accurate regional and/or global archeomagnetic field models (e.g. Pavón-Carrasco et al., 2014a,b). The acquisition of new archeointensity data dated to the Early Middle Ages is thus still necessary in order to build a detailed and continuous geomagnetic field intensity variation curve for Western Europe over the past 2000 years (Genevey et al., 2009, 2013).

We present here 19 new archeointensity data dated to the Early Middle Ages, among which 16 were obtained from the analysis of pottery fragments produced at Saran (Fig. 1a). This site, located a few kilometers north of the city of Orléans, France, was an important center of pottery production during the Middle Ages as evidenced by the numerous pottery kilns and associated ceramics found during excavations (Jesset et al., 2001, 2010; Jesset, 2013, 2015a,b; Bouillon, 2015). The archeointensity analysis of two groups of potsherds produced in Saran had previously been carried out by Genevey and Gallet (2002). These results are here reassessed in the light of new information provided by an experimental firing conducted on a reconstructed ancient kiln, which allowed a re-estimation of the cooling rate experienced by the ceramics. We further present intensity results obtained from modern pottery produced in known field conditions during this experimental firing.

2. Archeological collection

In the late sixties, when the archeological site of Lac de la Médecinerie was discovered in Saran (47.9°N, 1.9°N; Fig. 1a) and partially excavated (Chapotel, 1973), Emile Thellier sampled the kilns that were unearthed at the time. While being amongst the first structures analyzed in France for their archeomagnetic directions (Thellier, 1981), the Lac de la Médecinerie was the first archeological site revealing a medieval pottery activity in this city. Since then, other production units have been discovered at Saran and archeological excavations are still being conducted some 40 years later, in particular at the Lac de la Médecinerie site (Jesset et al., 2010). This on-going work has allowed Saran to be recognized as a major center of ceramic production in Central France during the Merovingian (5th–mid 8th century AD) and Carolingian (mid 8th–10th century AD) royal dynasties.

A detailed chrono-typology for the Saran production was constructed by crossing different information (e.g. Jesset, 2013, 2015b). It relies on constraints derived from the excavations conducted at Saran and also on various elements obtained from other sites where ceramics produced at Saran were discovered in a consumer context. These elements include radiocarbon dating, coins and historical constraints among others. The chronology is based on the recognition of the changing characteristics of pottery over time, such as the shape of the ceramics including the evolution of the lips, spout and the base, their function, the color and the texture of the paste, the overall quality of the production and also the decor, here often made with a small wooden wheel. The derived chronology runs from the 6th to the beginning of the 11th century AD. We only summarize below the major evolutionary trends of the ceramics produced at Saran, whose resolution allows dating with a precision of ±25 years in favorable cases. This should not hide the fact that the typo-chronology relies on the identification and integration of more elements than those presented here (Jesset, 2013, 2015b).

The beginning of ceramic production in Saran, during the 5th century AD, remains relatively unknown. Only a few grey shards with polished surfaces, fired in redox conditions and of Gallo-Roman appearance give evidence of some preliminary small-scale production. The 6th century AD is better documented; this period is characterized by forms and decors also inherited from the Gallo-Roman corpus, with thick walls (>5 mm) and by ochre-yellow clay paste with a light grey color at the core. The 7th century sees the reinforcement of the production activity and the expansion of its area of distribution, reaching a monoply position during the early 8th century through a region of 50–70 km around Saran. While most technological characteristics of the production do not change during the 7th century AD, such as the texture, the color and the thickness of ceramics, the production tends, however, to become more standardized due to the higher rate of production, with simpler decor and more rounded shapes. In contrast, the 8th century is characterized by significant evolution: the walls become thinner (3–4 mm) and the color of the pots darkened to red-ochre. The old forms are abandoned or evolve and new forms emerge. As an example, the trefoil tubular spout, which had appeared at the end of the 7th century, was at first separated from the neck of the pottery before gradually converging with it and finally fusing into it in the second half of the 8th century. A decline in quality of the ceramic production is also perceived during the second half of the 8th century, as evidenced by pots presenting defects discovered in consumer contexts. This decline continues during the 9th century, with a more reduced corpus of production, which foreshadows the end of the main workshops of Saran in the second part of the 9th century. For this period, the evolution of the shapes and of the lips of the globular pots serves as a chronological marker. The color of the ceramics dated to the 9th century is dark at first, before becoming brighter in the late 9th century, with a light ochre-yellow clay paste that characterizes the ceramics of the 10th century. The ceramics at this point are produced in small production units at Saran and the weaker activity likely favors an overall higher quality of the ceramics. Thicker walls are observed and a new profile of lips “en bandeau” appears during the second part of the 10th century, before the generalization of the latter during the 11th century, when, unfortunately, the ceramic production in Saran is no longer documented.

Considering only the groups of potsherds that successfully provided archeointensity results, our collection from Saran is composed of 17 groups encompassing the period from the 6th to the 10th century. They are mostly associated to two important production units excavated at the sites of Lac de la Médecinerie (6 groups) and La Guignace (7 groups), both situated along the old Roman road between Chartres and Orléans. Three other groups consist of pottery fragments from a smaller workshop excavated at the archeological site of Zac des Vergers, which had been in activity during Saran’s period of peak production. The last group, dated to the end of the 9th century, was sampled from a large set of ceramic fragments discovered during domestic building works in the current center of Saran (Saran le Bourg).

All fragments collected at Saran were found in pits inside or nearby the kilns where they were originally produced. They correspond to pottery wasters that were used to fill in the kilns after their abandonment. The selected fragments (as illustrated in Fig. 1b) are from units with a low level of pottery fragmentation and the potsherds show sharp (rather than eroded) sides. These are
good indicators that the fragments were thrown away soon after their production. For each group, the fragments are from one or two stratigraphic units associated to a single filling phase and were chosen to be representative of the ceramic materials, which allow dating of the filling phase. These groups are homogenous in terms of the granularity and color of the clay paste. In only one case, two successive filling events were sampled in one kiln and two distinct groups of potsherds were thus constituted (SAR13 and SAR14). We further note that the groups referred to as A36 and A38 were previously analyzed by Genevey and Gallet (2002). These old results are here reevaluated and group A36 has also benefited from a resampling (SAR08).

Fig. 1. (a) Location map of the three medieval archaeological sites of Saran, Ingré and Vanves sampled in this study (pink circles). The blue circles indicate the locations of our data previously obtained in France and for one result from Belgium (Genevey and Gallet, 2002; Genevey et al., 2009, 2013; Gallet et al., 2009). The green squares correspond to published intensity results available within a radius of 700 km and 1250 km around Paris (indicated by a red star). See text in section Geomagnetic field intensity variations in Western Europe over the past 1500 years, for a description of these selected data, which were obtained in Belgium, Denmark, England, France, Germany, Italy, Spain and Switzerland. (b) Photo illustrating a group of pottery fragments, as analyzed in this study. Here the SAR04 group collected at Lac de la Médecinerie in Saran associated to kiln F196. (c) Photo of pots discovered in the filling units of the kiln 1098 during excavations conducted in the street Rue Gaudray in Vanves. The VAN07 group is associated to this kiln © Laurent Petit, Iracap. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Sampling at Saran was complemented by other groups of pottery fragments produced elsewhere. A group was collected at Ingré (47.9°N, 1.8°E; Fig. 1a) about 10 km southwest of Saran. This site was a pottery workshop active during the 7th century. The production is characterized by a decor made with a punch, a practice rarely used in Saran. The ceramic corpus is, however, the same as that of Saran and the dating for this group thus relies on the same typo-chronology. Three groups of pottery fragments were also produced in Vanves (48.8°N, 2.3°E), a suburb to the south west of Paris (Fig. 1a). Excavations have revealed that Vanves was a major pottery production center for the region around Paris from the 6th to the 9th centuries, as was Saran for the central region of France. Excavations conducted in the street Rue Gaudray, in the historical center of Vanves, enabled the discovery of six pottery kilns close to each other, with several pits filled with failed ceramics (Lefèvre and Peixoto, 2015). Archeointensity results were already obtained from this site (Gallet et al., 2009). In the present study, we report on a new set of results from fragments collected in the filling layer in one of the six kilns, which is dated to between the middle of the 7th and the middle of the 8th century. This dating is based on typo-morphological evidence, such as the presence of fragments from large bowls with a small pinched spout and bowls with a wide band, both indicative of the end of the Merovingian period. We also note the presence of bi-conical vases, which were produced during the entire Merovingian period with an evolution over time from a fine, fumigated and polished paste to a granular production; this form then completely disappeared during the 8th century (Lefèvre, 2007). The collected fragments have a coarse paste with medium size inclusions (1–1.5 mm) and a color ranging from orange-beige to brown (Fig. 1c). Archeological data from another site (20 Place de la République) close to Rue Gaudray have documented the Early Medieval pottery production at Vanves, i.e. during the 6th century. No kiln was discovered but the potsherds found in different pits were undoubtedly identified as failed pottery. The shapes of these ceramics are characteristics of the 6th century AD, with flanged or carinated open forms and bi-conical pots (Lefèvre, 2009). Two fragment groups with the very same typo-morphological characteristics (having a coarse paste of light color with fine inclusions of less than 1 mm) and therefore having the same age, were collected from two pits (groups referred to as VAN04 and VAN05) and their archeomagnetic results will be discussed together.

3. Intensity and rock magnetic experiments

All experiments were carried out at the paleomagnetic laboratory of the Institut de Physique du Globe de Paris and the Laboratory of Structural and Molecular Archeology (LAMS) of Pierre et Marie Curie University, Paris. Intensity measurements were performed using Triaxe magnetometers (Le Goff and Gallet, 2004). The experimental protocol, derived from the Thellier and Thellier (1959) method, has been extensively described in previous studies (e.g. Gallet and Le Goff, 2006; Genevey et al., 2009; Hartmann et al., 2010) and we here present below only its key features and the main steps.

The Triaxe protocol involves continuous high-temperature magnetization measurements of a small specimen of ~1 cm in height and with a thickness depending on that of the fragment. It comprises a series of heating and cooling steps. In the first step, the Natural Remanent Magnetization (NRM) of the specimen is demagnetized between a low temperature T1 fixed at 150 °C and a high temperature T2, here fixed between 480 °C and 530 °C depending on the specimen. After the determination of the thermal variation between T1 and T2 of the NRM fraction still blocked above T2, a thermoremanent magnetization (TRM) is acquired by cooling down the specimen from T2 to T1 in a laboratory field whose intensity is chosen close to the expected value. The direction of the field is also adjusted in order to produce a TRM parallel to the NRM direction, which allows one to account for the TRM anisotropy effect (Le Goff and Gallet, 2004). This laboratory TRM is demagnetized by heating again the specimen from T1 to T2. From these different series of measurements, the ratios between the NRM and TRM fractions demagnetized between T1 and a running temperature Ti, every 5 °C, from T1 to T2 are computed and multiplied by the intensity of the laboratory field to obtain the R'(Ti) data (see in Le Goff and Gallet, 2004). The R'(Ti) data are finally averaged between T1 and T2 to obtain an archeointensity value at the specimen level. When a secondary magnetization component is observed above T1, the computations are performed over a reduced temperature interval (between T1' and T2') where only the primary TRM is demagnetized. Interestingly, as the Triaxe allows the acquisition of an almost full TRM in the same way as the NRM (instead of partial TRMs as in more classical intensity methods), the protocol limits the impact of the possible presence of multidomain grains on intensity determination. Furthermore, it was experimentally observed from analyses on a large collection of fragments that the Triaxe protocol allows overcoming the cooling rate effect on TRM acquisition (Le Goff and Gallet, 2004; Genevey et al., 2009; Hartmann et al., 2010, 2011).

The intensity determinations were evaluated through a set of quality criteria identical to those used in previous studies (for example Genevey et al., 2009). In particular, at the specimen level, the R'(Ti) data are averaged on a temperature interval over which only the primary magnetization component is isolated and which involves more than 50% of the magnetization remaining above the chosen temperature T1/T1', while the slope defined by the R'(Ti) values must be of less than 10%. The coherence of the intensity determinations is first tested from the analysis of two to three specimens per fragment, with an error in the mean intensity calculated at the fragment level that must be lower than 5%. A minimum of three intensity values determined at the fragment level (with fragments collected from different pots) is required to define a mean intensity value at the group level and the standard deviation of the latter must be lower than 10% and lower than 5 μT. It is worth recalling that the reliability of the Triaxe protocol and the pertinence of the applied quality criteria have been tested from cross comparison between intensity results obtained using classical intensity methods, with strict quality criteria, and the Triaxe procedure (Genevey et al., 2009; Hartmann et al., 2010, 2011). Nevertheless, the experimental firing performed in Saran, with modern pots produced in controlled thermal and magnetic field conditions, provided the opportunity to further attest to the reliability of the Triaxe archeointensity data and to offer new insights into the cooling rate effect.

In addition to the behavior observed during the Triaxe measurements, the stability of the magnetic mineralogy on heating, i.e. a basic request for intensity experiments, was also systematically tested through the reversibility of the heating and cooling curves of the low field magnetic susceptibility obtained using a KLY3 Kappabridge coupled with a CS3 furnace. In most cases, the maximum temperature for these experiments has been fixed at 500 °C because the NRM of the specimens is generally completely or almost completely demagnetized at this temperature.

For characterizing the magnetic mineralogy of the studied fragments, thermomagnetic susceptibility measurements were carried out up to ~680 °C on two fragments from each group. Further investigations were conducted on fresh specimens by the acquisition of Isothermal Remanent Magnetization (IRM) curves in fields up to a maximum of ~1T and of hysteresis loops using a Vibrating Sample Magnetometer (VSM). Thermal demagnetization of three-axis IRM (1.25T, 0.4T and 0.2T) acquired along three perpendicular
directions (Lowrie, 1990) was also performed on one fragment from each group, ensuring the reliability of the magnetic mineralogy. Finally, IRM acquisition up to 9T was conducted using a Magnetic Measurement Pulse Magnetizer MMPM10 on a set of six fragments selected according to the three-axis IRM results.

4. Experimental pottery firing at Saran: testing the triaxe protocol and re-evaluation of previous intensity data

An experimental pottery firing was performed on the 14th of November 2009 at the site of Lac de la Mèdecinerie (Millet et al., 2015). For this experiment, the well-preserved kiln F196 dated to the 9th century AD was chosen and reconstructed using local clay (Fig. 2a). This kiln is 4 m long and has a wide-open heating chamber, 1.3 m in diameter at the base and 1.10 m at the top. Kilns with an open heating chamber were most probably used during the whole period of activity in Saran. Here, the heating was conducted using two fires, one at the entrance of the kiln and the second above the heating chamber (Fig. 2a). The kiln is 4 m long and has a wide-open heating chamber (Fig. 2c). From an archaeological point of view, this experiment showed that the options chosen for the kiln reconstruction and the firing were appropriate. Indeed, the new ceramics appear very similar to the Saran production of the 7th century. This experiment also provided a rare opportunity to analyze modern ceramics produced in known thermal and magnetic field conditions, and thus to reassess the accuracy of the intensity determinations performed using the Triaxe protocol. For this, direct geomagnetic intensity measurements were carried out inside and outside the reconstructed kiln. A series of 55 measurements using a fluxgate magnetometer was conducted inside the kiln when first full of pottery, then half loaded and finally completely empty, with measurement points located close to the ceramics, kiln walls and under the vessel chamber. All measurements were very homogeneous, yielding a mean intensity value of 47.4 ± 0.4 μT. Twenty additional measurements were performed from about 10 m to 40 m in the vicinity of the kiln. They yielded a nearly identical mean intensity value (47.9 ± 0.5 μT), also very close to the geomagnetic field intensity measured in the French geomagnetic observatory at Chambon la Forêt (47.7 μT), about 20 km northeast of Saran. All these direct measurements show that the kiln and its load do not induce a significant magnetic anomaly, and thus the intensity measured inside the kiln correctly reflects the Earth’s magnetic field intensity at Saran. Note that a similar conclusion was reached by Morales et al. (2011) from direct magnetic measurements performed around and inside a small original and open artisanal kiln analyzed in Mexico.

Intensity experiments were conducted on 6 modern pots with two specimens analyzed per pottery (group SAR00). Ten additional pots were tested but the specimens were found to be too weakly magnetized to be analyzed using the Triaxe (i.e. with a moment of less than 40 10⁻⁸ A.m²; note that our sampling could not be extended as the pots are to be exhibited). Magnetic susceptibility, IRM acquisition, hysteresis and three-axis IRM measurements were also carried out on this modern material, and the results will be discussed below together with those obtained from the ancient ceramics. The intensity results obtained on the 6 analyzed pottery satisfy our set of quality criteria. As per usual, the intensity results have been first averaged at the specimen level, then at the fragment level, and finally at the group level. This yields a mean intensity value of 46.6 ± 1.2 μT (Table 1), which is in good agreement with the direct intensity measurements performed inside and nearly the kiln. This test thus highlights two points: the reliability of the experimental protocol developed for the Triaxe magnetometer and the great potential of the ceramic production at Saran for...
characterizing the geomagnetic field intensity variations during the Early Middle Ages.

The temperature measurements performed during the experimental firing were also used for assessing the cooling rate effect on TRM acquisition in the case of intensity determinations derived from a more classical method (Genevey and Gallet, 2002). They showed that for this type of rather small kiln with an open heating chamber, the cooling was very rapid, with temperatures decreasing from 1000 °C to 50 °C in less than five hours (Fig. 2c). This observation led us to reconsider the intensity results previously obtained from two groups of ceramics produced at Saran (Genevey and Gallet, 2002). We recall that these data were obtained using the Thellier and Thellier (1959) method as revised by Aitken et al. (e.g. 1988; hereafter referred to as TT-IZ method) and the cooling rate correction was determined from the comparison of two TRMs acquired from 450 °C to room temperature (Fig. 2c). We have reanalyzed all fragments successfully studied in 2002, plus two fragments, which were rejected because of alteration detected during the cooling rate experiments but not during the intensity measurements (with positive checks for the stability of the partial thermoremanent magnetization, i.e. positive pTRM-checks). We point out that the cooling rate experiments and the intensity measurements were not performed on the same specimens. For the two previously rejected fragments, the new experiments were successful (i.e. no alteration detected), allowing us to consider them now for intensity determination. Overall, these new cooling rate experiments demonstrate that the cooling rate corrections applied in 2002 were overestimated by 1–6%. Using the new corrections, we thus revised the two intensity values previously obtained at Saran (supplementary Table S1).

In addition, Triaxe intensity measurements were carried out on four fragments from the same groups. Here we were limited by the relatively weak magnetization of the fragments and by the fact that there was sometimes not enough material for new measurements. Hence only two fragments from group A36 and two from group A38 allowed a direct comparison between Triaxe and TT-IZ intensity results. At the fragment level, three fragments out of four yield similar intensity values to within 2.5% (supplementary Table S1).

Table 1

<table>
<thead>
<tr>
<th>#Group</th>
<th>Age (A.D.)</th>
<th>Site (Location, Archeological excavation)</th>
<th>Archeological description</th>
<th>N Frag. (n Spec.)</th>
<th>$F \pm \sigma F$ (μT)</th>
<th>$F_{\text{ran}}$ (μT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAN04/VAN05</td>
<td>525–575</td>
<td>Vanves, rue de la République</td>
<td>Pits 2 &amp; 6 (SU 1023 &amp; SU 1039 &amp; SU 2008)</td>
<td>N = 4 (n = 8)</td>
<td>73.6 ± 1.8</td>
<td>73.6</td>
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<tr>
<td>SAR16</td>
<td>550–600</td>
<td>Saran, Lac de La Médecinerie</td>
<td>Kiln V</td>
<td></td>
<td></td>
<td>Kiln 258 (SU 1359)</td>
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<tr>
<td>SAR18</td>
<td>550–600</td>
<td>Saran, La Guignace</td>
<td>Pit F313 (SU 1456)</td>
<td>N = 8 (n = 16)</td>
<td>77.1 ± 1.9</td>
<td>77.9</td>
</tr>
<tr>
<td>SAR12</td>
<td>550–600</td>
<td>Saran, Lac de La Médecinerie</td>
<td>Kiln U</td>
<td></td>
<td></td>
<td>Kiln 258 (SU 1410)</td>
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<td>SAR20</td>
<td>575–625</td>
<td>Saran, La Guignace</td>
<td>Kiln 7 (SU 3024)</td>
<td>N = 8 (n = 16)</td>
<td>78.5 ± 2.5</td>
<td>79.3</td>
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<td>625–675</td>
<td>Saran, Lac de La Médecinerie</td>
<td>Kiln W</td>
<td></td>
<td></td>
<td>Kiln 185/186 (SU 1399 &amp; SU 1575)</td>
</tr>
<tr>
<td>SAR14</td>
<td>625–675</td>
<td>Saran, Lac de La Médecinerie</td>
<td>Kiln W</td>
<td></td>
<td></td>
<td>Kiln 185/186 (SU 1517)</td>
</tr>
<tr>
<td>SAR13+SAR14</td>
<td>625–675</td>
<td>Saran, Lac de La Médecinerie</td>
<td>Kiln W</td>
<td></td>
<td></td>
<td>Kiln 185/186 (SU 1399 &amp; SU 1575 &amp; SU 1517)</td>
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<td>SAR22</td>
<td>625–675</td>
<td>Saran, La Guignace</td>
<td>Kiln 9 (SU 2731)</td>
<td>N = 8 (16)</td>
<td>76.1 ± 1.5</td>
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<td>ING01</td>
<td>600–700</td>
<td>Ingré</td>
<td>Pit</td>
<td>N = 5 (n = 11)</td>
<td>77.6 ± 0.9</td>
<td>78.4</td>
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<td>650–700</td>
<td>Saran, La Guignace</td>
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<td>N = 7 (n = 14)</td>
<td>78.0 ± 1.3</td>
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<td>VAN07</td>
<td>650–750</td>
<td>Vanves, Rue Gaudray</td>
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<td>A36/SAR08</td>
<td>675–725</td>
<td>Saran, Zac des Vergers</td>
<td>Kiln 256/2230 (SU 2065 &amp; SU 2066)</td>
<td>N = 12 (n = 29)</td>
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<td>Saran, La Guignace</td>
<td>Kiln 11 (SU 1605)</td>
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<td>Saran, Zac des Vergers</td>
<td>Kiln 1148/1242/2319 (SU 10485 &amp; SU 10608)</td>
<td>N = 6 (n = 12)</td>
<td>76.9 ± 3.1</td>
<td>77.7</td>
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<tr>
<td>SAR05</td>
<td>800–850</td>
<td>Saran, Zac des Vergers</td>
<td>Kiln 2690 (SU 21636 &amp; SU 21637)</td>
<td>N = 5 (n = 10)</td>
<td>78.3 ± 2.6</td>
<td>79.1</td>
</tr>
<tr>
<td>SAR27</td>
<td>800–850</td>
<td>Saran, La Guignace</td>
<td>Kiln 3 (SU 1892)</td>
<td>N = 7 (n = 14)</td>
<td>80.1 ± 3.8</td>
<td>80.9</td>
</tr>
<tr>
<td>A38</td>
<td>800–850</td>
<td>Saran, Lac de La Médecinerie</td>
<td>Kiln E</td>
<td>N = 4 (n = 12)</td>
<td>79.0 ± 1.9</td>
<td>79.8</td>
</tr>
<tr>
<td>SAR04</td>
<td>800–850</td>
<td>Saran, Lac de La Médecinerie</td>
<td>Kiln M</td>
<td></td>
<td></td>
<td>Kiln 196 (SU 1467 &amp; SU 1347)</td>
</tr>
<tr>
<td>SAR10</td>
<td>850–950</td>
<td>Saran, le Bourg</td>
<td>Working area</td>
<td>N = 4 (n = 9)</td>
<td>76.4 ± 2.3</td>
<td>77.1</td>
</tr>
<tr>
<td>SAR00</td>
<td>14/11/2009</td>
<td>Saran, Lac de La Médecinerie</td>
<td>Experimental firing</td>
<td>N = 6 (n = 12)</td>
<td>46.6 ± 1.2</td>
<td>47.1</td>
</tr>
</tbody>
</table>
For fragment A38-06, the Triaxe intensity value appears about 7% higher than the TT-IZ value (79.9 μT versus 73.8 μT), even after the reevaluation of the cooling rate correction. This may be due to differences in the cooling rate experienced by the pottery with respect to their position in the kiln as discussed by Morales et al. (2011). In this case, the duration of 4 h for the cooling time from 450 °C would be too long. Another option would be a bias in the heating and blue/cooling curves. (a–e) Medieval pottery fragments; (f) Pottery produced during the experimental firing. The heating was first performed up to 500 °C, then another heating up to 500 °C was next conducted on new powders (black axis; black/heating and grey/cooling curves). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The aim here is to characterize the magnetic mineralogy of the pottery fragments fulfilling the quality criteria considered for our archeointensity experiments. All these fragments display reversible susceptibility curves after heating to 500–550 °C (Fig. 3). When heating is conducted to 700 °C, the χ(T) curves are still reversible, even though a limited alteration is observed in some potsherds (Fig. 3). Most of the χ(T) curves show a single inflection point between 520 °C and 570 °C, while another inflection point between 200 °C and 300 °C is only observed in a few cases (Fig. 3e).

The saturation of the magnetization is never reached in a field of 1T (Fig. 5a). However, the hysteresis loops are only rarely constricted (Fig. 5b–d). The three-axis IRM experiments clearly show for most fragments the predominance of a magnetic mineral of low coercivity (<0.2T) and unblocking temperatures of less than 550 °C, which are typical of magnetite with possible impurities (Fig. 4a,b). We note that the presence of titanium was observed for the Saran production from inductively coupled plasma atomic emission spectroscopy (Bocquet-Liénard and Birée, 2014). The hard components (0.4T and 1.25T) indicate the presence in variable proportions of a mineral of high coercivity, whose unblocking temperatures range between 200 °C and 250 °C (Fig. 4a–f). We note that this mineral, whose precise identification is still debated (Mcintosh et al., 2007, 2011), is quite frequent in archeological baked clay fragments, whatever their age and their geographic origin (e.g. Chauvin et al., 2000; Genevey and Gallet, 2002; Hartmann et al., 2011). Furthermore, a behavior more typical to that of (titanio)hematite is observed for most samples from the thermal demagnetization of the hard component between 550 °C and 650 °C (Fig. 4d–f). But this magnetic phase is only present in small amounts as it was not detected from the susceptibility measurements (Fig. 3).

5. Magnetic mineralogy

The aim here is to characterize the magnetic mineralogy of the pottery fragments fulfilling the quality criteria considered for our archeointensity experiments. All these fragments display reversible susceptibility curves after heating to 500–550 °C (Fig. 3). When heating is conducted to 700 °C, the χ(T) curves are still reversible, even though a limited alteration is observed in some potsherds (Fig. 3). Most of the χ(T) curves show a single inflection point between 520 °C and 570 °C, while another inflection point between 200 °C and 300 °C is only observed in a few cases (Fig. 3e).

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![Fig. 3. Representative examples of magnetic susceptibility versus temperature curves obtained for fragments fulfilling the quality criteria used for intensity determinations.](image)

(a–e) Medieval pottery fragments; (f) Pottery produced during the experimental firing. The heating was first performed up to 500 °C–550 °C (blue axis in the insets; red/heating and blue/cooling curves). Another heating up to ~680 °C was next conducted on new powders (black axis; black/heating and grey/cooling curves). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Our experiments were complemented by a set of IRM data acquired up to 9T from six fragments. Two of which are representative of the majority of the collection, i.e. with a magnetization predominantly carried by the (titano) magnetite phase (Fig. 4 a,b), whereas the four other fragments contain in a relatively large proportion the mineral of high coercivity and low unblocking temperatures previously characterized from the three-axis IRM results (Fig. 4 c–f). In all cases, the magnetization saturation is reached at around 3.5T (Fig. 4g). On the other hand, the behavior between ~0.2T and ~3T is entirely controlled by the ratio between the high-coercivity and the (titano) magnetite phases (Fig. 4g). For the weak ratios (SAR08-19), a first plateau is seen below 0.3T and corresponds to the saturation of the magnetite phase, while for the large ratios (SAR25-05, SAR18-11), no plateau is observed.

Finally, it is worth mentioning that the magnetic mineralogy of the fragments (including those from the modern production) that provided accepted archeointensity data, appears very similar to that encountered in our previous studies (Genevey and Gallet, 2002; Genevey et al., 2009, 2013). The magnetization is hence dominated by (titano) magnetite that conveys the geomagnetic information. It further involves a varying fraction of a magnetic phase characterized by low-unblocking temperatures (200–250 °C) and high coercivity (~3.5T), as well as traces of a more standard hematite demagnetized above ~550 °C.

6. Intensity results

The success rate of the Triaxe measurements varies among the different fragment groups, ranging from 24% to 89%. All the intensity results obtained at the specimen level (with a total of 276 specimens from 134 independent fragments) are reported in the supplementary Table S2. We note that this success rate is relative to the number of fragments whose magnetization was sufficiently strong to be analyzed using the Triaxe magnetometer. In some cases, this limitation has significantly reduced the number of fragments available for intensity measurements (supplementary Table S2). The intensity results from 7 groups, plus those obtained from the modern pots are displayed in Fig. 5 (one panel per group). In this representation, each curve represents R(T) data obtained for one specimen leading on average to a mean intensity value at the specimen level. For each group, the individual curves appear coherent both at the specimen and fragment levels, which allows us to compute a precise group-mean intensity value with a standard deviation of less than 5% (Table 1).

It is worth pointing out that for the two groups SAR13 and SAR14, associated with two different filling phases inside the same kiln but sharing the same archeological dating, the two mean intensity values are in very good agreement (Table 1). This indicates that the time interval between the two filling phases was most probably short. For this reason, we averaged together all the results from these two groups to obtain a single mean intensity value for the composite group SAR13 + SAR14 (Table 1).

One of the main causes of rejection in our intensity experiments was related to the overlapping of two components of magnetization making it difficult to reliably isolate a primary magnetization component (Fig. 6a). This observation indicates that some pots broke during the manufacturing process. In fact, this type of incident principally occurs during the early stage of firing because of a very rapid temperature increase inducing stresses in the clay. The presence of
two magnetization components in some fragments could therefore indicate reorganization or rebalancing of the load during cooling (the ceramics being somewhat randomly stacked in the kiln – Fig. 2b), with fragments from broken pots moving abruptly or progressively. However, we underline that, for a certain number of fragments, this complexity did not prevent the determination of a reliable archeointensity value (Fig. 5, 6b and supplementary Table S2).
Several groups of fragments from Saran were also rejected either because the results did not satisfy our quality criteria or because the fragments were too weakly magnetized to achieve measurements using the Triaxe. This has, unfortunately, been the case for two groups associated to the last period of production in Saran (end of the 10th century and beginning of the 11th century). Another group of fragments from the early phase of ceramic production at Saran (middle of the 6th century) was excluded because the original heating (and cooling) was performed in redox conditions; being conducted in air (i.e. in oxidizing conditions), our intensity experiments therefore led to an alteration of the magnetic mineralogy with a clear lightening of the clay paste (a color similar to that of the later production). Four groups dated to the 9th century AD were also discarded because of a non-ideal magnetic behavior during the intensity determination (i.e. our quality criteria were not fulfilled). The preparation of these particular specimens revealed a soft paste during drilling. As these groups are from the period when the quality of Saran production had declined, it is tempting to relate our failed intensity determinations to this loss of quality. Another possibility, however, would be a relationship with the technical evolution observed from the middle of the 8th century in the morphology of the kilns. This evolution is marked by a kiln floor, which is no longer horizontal but inclined in order to improve the circulation of hot air, which is most probably accompanied by a less open heating chamber (Jesset, 2015a).

Our new archeointensity data for the Early Middle Ages are plotted in Fig. 7. They show that this period was characterized by a rapid intensity increase during the 6th century AD, before a high level of intensity (almost twice that of the present-day field) between the 7th and the 9th century. However, a relative intensity minimum, here documented by two intensity data, likely occurred at the transition between the 7th and the 8th century. Finally a rapid intensity decrease occurred from the middle of the 9th to the beginning of the 11th century, whose averaged variation rate, of the order of $-0.10 \, \mu T/\text{year}$, is similar to the one observed during the 6th century. We note that this value is similar to the maximum variation rate observed in the present-day geomagnetic field (Livermore et al., 2014).

7. Geomagnetic field intensity variations in Western Europe over the past 1500 years

In Western Europe, the variations in geomagnetic field intensity during the Early Middle Ages have long remained poorly documented. Several studies, however, have improved this situation (e.g. Genevey and Gallet, 2002; Donadini et al., 2008, 2012; Gómez-Paccard et al., 2012). This study contributes to this effort with 19 new archeointensity data from the 6th to the 10th century AD, which allows us to decipher the intensity variations over the past 1500 years. Here we discuss that evolution using the archeointensity data obtained in two circular areas centered on Paris. The first is an area with a 700 km radius around Paris (the geographical area covered by our data), while the second region, with a radius of 1250 km, allows us to significantly increase the geographical area covered by our data), while the second region, with a radius of 1250 km, allows us to significantly increase the dataset with, in particular, the inclusion of numerous results from Spain (e.g. Gómez-Paccard et al., 2006, 2008, 2012; Fig. 1a). For the area of radius 700 km, we have further proceeded in two steps; first considering only our results, which form a homogeneous collection of data, and then all the results available within this area fulfilling a set of selection criteria (see below).

Our data collection comprises 70 intensity results dated from the 5th to the middle of the 19th century (Genevey and Gallet, 2002; Gallet et al., 2005, 2009; Genevey et al., 2009, 2013 and this study), which share many common characteristics. One concerns their age uncertainties, which are always of less than 100 years (this is a selection criterion for our sampling). But, in most cases (i.e. 60 data), the dating precision is less than 50 years. A large majority of the data was obtained using the Triaxe protocol alone or combined with data derived using more classical intensity procedures (in this case, with an agreement within $\pm 5\%$ between the
 Following Genevey et al. (2008, 2009, 2013), an arbitrary 5% decrease was implemented for the data, indicated by 

respective means). Only five groups of fragments from this collection were analyzed using solely the TT-IZ (Aitken et al., 1988) or TT-IZZI (Yu et al., 2004) protocols. Finally, the quality criteria used to retain the mean intensity values have remained unchanged throughout our different studies, which further contributes to the homogeneity of this dataset.

The different datasets discussed above are displayed in Fig. 7 together with the corresponding master curves. When considering only our collection of data, the derived master curve clearly shows the occurrence of five intensity maxima, at the transition between the 6th and 7th century AD, at the middle of the 9th century, during the 12th century, in the second part of the 14th century and at the very beginning of the 17th century (Fig. 7a and Table 2; see also

appearing as outliers. The method includes a bootstrap approach to account for the experimental and age uncertainties of the data. From the bootstrap resampling technique, the code estimates a large ensemble of individual maximum likelihood curves (about 60,000), reconstructs the probability density distribution (pdf) of the maximum likelihood, and then displays its variability at 95% (i.e. the envelope containing 95% of the individual curves) and a 95% confidence interval obtained using a classical least-squares inversion. In addition, the self-consistency of the data uncertainties is explored for each model through the computation of the normalized root mean square (NRMS) that evaluates the ratio between the \( a \) posteriori and \( a \) priori errors assumed for the data (i.e. the ratio between the distance of the data to the model and the original error attached to the data). It is important to stress that the bootstrap resampling method aims at enhancing only the patterns appearing as outliers.
Genevey et al., 2013). That computation is characterized by a mean NRMS of 1.10 ± 0.12, which underlines the self-consistency between the a priori and a posteriori data uncertainties. In this case, the 95% fluctuation envelope and the 95% confidence interval match almost perfectly (Fig. 7a). The incorporation of 22 data acquired in the same geographical area (i.e. 700 km around Paris; Fig. 1a) does not markedly change the previous description of the field behavior (Fig. 7b,e and Table 2). However, the mean NRMS for this curve is larger (1.43 ± 0.13), which indicates that the model could not fit all data within their a priori errors. This is also expressed in Fig. 7b by the fact that the 95% confidence interval becomes wider than the 95% fluctuation envelope of the master curve. Nevertheless, the additional data allow to better document both the significant increase and decrease in geomagnetic field intensity that bound (and characterize) the Early Medieval period, whereas our new data tend to reduce the amplitude of the intensity variations previously suggested by Gómez-Paccard et al. (2012), in particular with a less pronounced relative intensity minimum at the transition between the 7th and the 8th century AD.

Regarding the data reported in Gómez-Paccard et al. (2012), one was obtained in Saran from a series of bricks from kiln F256 excavated at the Zac des Vergers site (laboratory code 45302A; mean intensity at Paris: 80.6 ± 8.3 µT). After its abandonment, the kiln was filled with pottery fragments, whose typo-morphology was used to determine its dating. In this study, we analyzed a group of potsherds (A36/SAR08) found in this filling, which gave a mean intensity at Paris of 72.7 ± 3.6 µT (Table 1). Although the two intensity results are compatible within their error bars, we cannot exclude the fact that the field intensity during the last use of the kiln was slightly higher than the intensity at the time of production of the pottery found inside the kiln (we further note that Gómez-Paccard et al. (2012) applied a slow cooling time of 24 h for correcting their data from kiln F256 which, according to the experimental firing described in this study, may lead to an underestimated mean intensity value). This difference is in agreement with the moderate decrease in intensity observed between the early 7th century and the transition between the 7th and 8th century (Fig. 7a,b). We note, however, that a time lag between the two contexts is not the most likely option from an archeological point of view.

Further extending the geographical area of the data to 1250 km (Fig. 1a, 7c) does not have any real impact on the reconstruction of the intensity evolution during the Early Medieval period because only three results are added to the previous dataset. By contrast, the number of results dated after the 10th century is significantly increased (Fig. 7e). In particular, the dataset now includes the numerous results obtained in Lübeck (Germany; Schnepf et al., 2009), whose dating was constrained by a time-sequential relationship based on the stratigraphy. It is worth mentioning that this chronology was taken into account for the computation of the probability density function (as was also the case for data obtained by Gómez-Paccard et al., 2006, 2008). As previously discussed in Genevey et al. (2009, 2013), the extended dataset provides a master curve characterized by smooth fluctuations between ~1200 and 1600 AD, which is due to the scatter between the data. Here the degraded internal consistency of the dataset, considered as a whole, is expressed by a NRMS of 1.71 ± 0.13. This dispersion most probably arises from underestimated experimental uncertainties and/or dating errors for some data, as well as from a possible (though likely limited) effect due to secular variation within the rather large geographical area of concern (Casas and Incoronato, 2007). Not surprisingly, introducing a selection criterion of the data based on the dating precision (i.e. within 100 years) decreases the NRMS to 1.63 ± 0.13 and we can better recognize the intensity peaks observed in Fig. 7a,b (Genevey et al., 2013).

This table lists the maximum likelihoods of the Western European geomagnetic field intensity variation estimated at Paris from 400 to 1850 AD years and their 95% fluctuation intervals computed in steps of 25 years. These computations rely firstly on our data and secondly on data available within 700 km around Paris fulfilling selection criteria (see text). They were carried out using the iteratively re-weighted least squares method combined with a bootstrap algorithm developed by Thébault and Gallet (2010).

![Table 2](image-url)
Ages, do not change the main conclusions, in particular regarding the detection from the field models of three intensity maxima observed in Western Europe from the 11th century onwards (Fig. 8a–e, where geomagnetic field models only incorporating volcanic and archeological data were used: Pavón-Carrasco et al., 2009, 2014b; Korte et al., 2009; Licht et al., 2013). The regional field modeling constructed by Pavón-Carrasco et al. (2009), that was derived without the archeointensity data obtained by Gómez-Paccard et al. (2012), provides the best evidence for the succession of five intensity maxima since the fifth century AD (Fig. 8a,e). Only the amplitude of the intensity peak at the transition between the 6th and 7th century AD differs significantly. These models were principally constrained by the intensity data obtained in Eastern Europe, mainly in Bulgaria where the dataset was recently updated (Kovacheva et al., 2014). Following Tema and Kondopoulou (2011), we selected the data available within a radius of 700 km around Thessaloniki. Furthermore, as in Genevey et al. (2013), we released the selection criterion relying on the use of pTRM-checks for testing the thermal stability of the magnetic mineralogy of the studied archeological artifacts. Otherwise this would have led to the rejection of a large proportion of this collection of data; it is worth recalling that the same approach applied to the Western European data set would not alter the results shown in Fig. 7. The resulting Balkan master curve given in Fig. 8f shows a series of intensity maxima more or less in phase with that from Western Europe, except for the peak around 850 AD in Western Europe (Fig. 8a,f). Moreover, the amplitudes of the relative maxima significantly differ between the two European regions. At this stage, we note that searching for evidence of a westward drift in geomagnetic field intensity fluctuations from a comparison between Figs. 8a and f appears inconclusive, or at least premature.

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recurrence of these peaks. This can be quantified using a Fourier analysis, which indicates the occurrence of a signal with a pseudo period of ~250 years (Fig. 9). It is worth mentioning that this period is data-driven, based on a coherent dataset, and not introduced by the modeling procedure. We venture that this feature betrays a genuine characteristic of the secular variation, at least in Western Europe, which could be related to a wave motion in the liquid core (e.g. Finlay and Jackson, 2003; Buffett, 2014). In any case, it will require further testing, in particular by continued data acquisition from older periods for which the present scatter observed between the available data prevents a robust analysis (e.g. Gallet et al., 2009; Pavón-Carrasco et al., 2014a).

8. Conclusions

The results of this study can be organized around five main points:

1. A good agreement is obtained between directly measured geomagnetic field intensities inside or in the periphery of an ancient kiln reconstructed for an experimental firing and the mean intensity value derived from the analysis of pottery produced during this firing. Such agreement confirms and strengthens the reliability of the experimental protocol (and of our selection criteria) developed for the Triaxe magnetometer. This also demonstrates the potential of the ceramic production at Saran to recover the geomagnetic field intensity variations during the Early Middle Ages.

2. Our data show that the magnetic mineralogy of the pottery produced at Saran between the 6th and the 10th century AD is dominated by magnetite, which may have titanium impurities. Another magnetic phase characterized by high coercivity and low unblocking temperatures (200°–250 °C) is often present in various proportions. Here we show that this phase is saturated in fields of about 3.5T.

3. We obtain 19 new archeointensity data spanning the Early Middle Ages, a period which was until now very poorly documented in Western Europe. The geomagnetic field intensity variations are characterized by a rapid increase during the 6th century AD, then by high intensity values from the 7th to the 9th centuries and finally by a strong decrease until the beginning of the 11th century. A minimum in intensity of small amplitude is also observed at the transition between the 7th and the 8th century AD.

4. We construct a master curve covering the past 1500 years using a selection of data obtained within 700 km around Paris. This curve clearly exhibits five intensity maxima, at the transition between the 6th and the 7th century AD, at the middle of the 9th century, during the 12th century, in the second part of the 14th century and at the very beginning of the 17th century AD. Some of the peaks are smoothed, or nearly absent when the selection of the data is extended to a radius of 1250 km around Paris.

5. We note that the intensity peaks observed in Western Europe over the past 1500 years occur every ~250 years. This regularity, unnoticed until now, might reflect a new characteristic of the secular variation, at least in Western Europe. It clearly requires further testing, in particular focusing on older periods.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pepi.2016.06.001.

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Figure S1
### Table S1.

| Potsherd | Samples | n  | $T_{min}$ | $T_{max}$ | F | g | q | F0 | F0 corrected | oF | F anisotropy corrected | Cooling rate correction factor - Slow cooling time of 10 hours from 450°C | $F_{mean}$ & $F_{mean}$±σ (TT-ZI) | Cooling rate correction factor - Slow cooling time of 4 hours from 450°C | $F_{mean}$ & $F_{mean}$±σ (TT-ZI) | This study | $F_{mean}$ & $F_{mean}$±σ (TT-ZI) | $F_{mean}$ & $F_{mean}$±σ (TT-ZI) |
|----------|---------|----|-----------|-----------|---|---|---|----|--------------|----|------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|-------------------------------|-----------------------------|-----------------------------|
| A36-01   | X317    | 13 | 150-500   | 0.89      | 0.89 | 51.57 | 60.0 | 66.5 | 1.0 | 69.5 | 0.92 | 62.5±1.7 | 0.98 | 66.5±1.7 |
| A36-03*  | X325    | 6  | 375-500   | 0.62      | 0.79 | 19.18 | 60.0 | 67.3 | 1.7 | 74.7 | X | X | 1.00 | 74.4±0.3 | 73.9±0.6 |
| A36-05   | X328    | 11 | 250-500   | 0.69      | 0.90 | 38.73 | 60.0 | 63.4 | 1.0 | 69.1 | 0.93 | 64.9±0.7 | 0.97 | 67.7±0.7 | 68.2±1.1 | 68.9±3.1 | 71.1±2.9 |
| A36-06   | X334    | 11 | 250-500   | 0.81      | 0.86 | 45.98 | 60.0 | 64.6 | 1.0 | 71.7 | 0.91 | 64.3±1.0 | 0.97 | 68.6±1.0 |
| A36-08   | X338    | 14 | 100-500   | 0.86      | 0.90 | 88.93 | 60.0 | 68.9 | 0.6 | 69.2 | 0.90 | 63.1±0.9 | 0.96 | 67.2±0.9 |
| A36-09   | X339    | 11 | 250-500   | 0.80      | 0.88 | 62.45 | 60.0 | 68.8 | 0.8 | 70.9 | | | | | |
| A38-02   | X250    | 13 | 150-500   | 0.88      | 0.91 | 47.41 | 60.0 | 83.5 | 1.4 | 82.2 | 0.93 | 76.1±0.5 | 0.99 | 80.9±0.5 |
| A38-03*  | X253    | 11 | 250-500   | 0.83      | 0.84 | 57.20 | 60.0 | 74.9 | 0.9 | 80.9 | X | X | 0.96 | 79.1±1.5 | 81.1±0.7 |
| A38-04   | X254    | 11 | 250-500   | 0.83      | 0.84 | 38.52 | 60.0 | 73.2 | 1.3 | 83.8 | 0.94 | 77.3±0.4 | 74.7±3.5 | 0.95 | 78.1±0.4 | 78.0±3.0 | 80.5±0.6 |
| A38-06   | X260    | 11 | 150-450   | 0.66      | 0.88 | 35.39 | 60.0 | 66.6 | 1.1 | 82.6 | | | | | | |
| A38-06   | X265    | 13 | 150-500   | 0.82      | 0.90 | 44.09 | 60.0 | 76.7 | 1.3 | 78.2 | 0.91 | 70.7±0.5 | 0.95 | 73.8±0.5 | 79.9±0.4 |
| A38-06   | X267    | 13 | 150-500   | 0.81      | 0.90 | 43.47 | 60.0 | 74.6 | 1.3 | 77.2 | | | | | | |

**Note:** Values are mean ± standard deviation.
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**SAR20, Saran, La Guignace, [575-625] AD, (16/14/8)**

| SAR20-03 | SAR20-03A | 185-485 | 75 | 88 | -2 | 76.2 | 77.2±1.0 |
| SAR20-03B | 200-485 | 75 | 84 | -4 | 78.2 |        |
| SAR20-04 | SAR20-04A | 240-485 | 75 | 86 | -1 | 81.3 | 81.3±0.1 |
| SAR20-04B | 240-475 | 75 | 79 | 4 | 81.2 |        |
| SAR20-06 | SAR20-06A | 180-490 | 75 | 86 | 4 | 75.2 | 76.0±0.8 |
| SAR20-06B | 180-475 | 75 | 80 | -2 | 76.7 |        |
| SAR20-07 | SAR20-07A | 180-485 | 75 | 91 | -2 | 77.9 | 79.4±1.5 |
| SAR20-07B | 180-475 | 75 | 89 | -2 | 80.8 |        |
| SAR20-09 | SAR20-09A | 180-485 | 75 | 87 | 0 | 78.3 | 78.2±0.2 |
| SAR20-09B | 190-475 | 75 | 78 | -4 | 78.0 |        |
| SAR20-10 | SAR20-10A | 225-485 | 75 | 80 | -6 | 75.9 | 76.2±0.3 |
| SAR20-10B | 230-485 | 75 | 80 | 1 | 76.4 |        |
| SAR20-14 | SAR20-14A | 255-485 | 75 | 85 | 0 | 83.0 | 83.0±0.0 |
| SAR20-14B | 275-475 | 75 | 80 | 4 | 83.0 |        |
| SAR20-15 | SAR20-15A | 175-475 | 75 | 79 | 0 | 76.5 | 76.9±0.4 |
| SAR20-15B | 175-475 | 75 | 79 | 2 | 77.2 |        |

**SAR13, Saran, Lac de La Medecinerie, [625-675] AD, (27/21/11)**

<p>| SAR13-04 | SAR13-04A | 180-500 | 75 | 90 | 5 | 79.8 | 78.3±1.5 |
| SAR13-04B | 180-495 | 75 | 91 | 3 | 76.8 |        |
| SAR13-08 | SAR13-08A | 340-505 | 75 | 94 | 4 | 81.5 | 80.8±0.8 |
| SAR13-08C | 375-510 | 75 | 90 | 4 | 80.0 |        |
| SAR13-09 | SAR13-09A | 305-510 | 75 | 75 | 5 | 83.2 | 83.3±0.1 |
| SAR13-09B | 325-495 | 75 | 84 | 3 | 83.3 |        |
| SAR13-13 | SAR13-13A | 175-510 | 75 | 90 | -5 | 76.0 | 75.6±0.6 |
| SAR13-13D | 180-470 | 75 | 91 | -3 | 75.1 |        |
| SAR13-14 | SAR13-14A | 245-510 | 75 | 92 | 5 | 74.1 | 75.2±1.1 |
| SAR13-14B | 250-500 | 75 | 87 | 5 | 76.3 |        |
| SAR13-16 | SAR13-16A | 220-510 | 75 | 95 | 6 | 77.0 | 76.9±0.2 |
| SAR13-16C | 225-500 | 75 | 91 | 1 | 76.7 |        |
| SAR13-18 | SAR13-18A | 205-510 | 75 | 90 | 5 | 75.4 | 76.3±0.9 |
| SAR13-18B | 225-500 | 75 | 91 | 5 | 77.2 |        |
| SAR13-19 | SAR13-19A | 220-510 | 75 | 92 | 2 | 76.2 | 75.8±0.4 |
| SAR13-19B | 180-500 | 75 | 85 | -4 | 75.4 |        |
| SAR13-20 | SAR13-20A | 200-495 | 75 | 96 | -1 | 76.4 | 76.3±0.2 |
| SAR13-20C | 200-485 | 75 | 93 | 1 | 76.1 |        |
| SAR13-22 | SAR13-22A | 175-500 | 75 | 95 | 3 | 77.3 | 77.3±0.0 |
| SAR13-22B | 200-500 | 75 | 94 | -1 | 77.3 |        |
| SAR13-25 | SAR13-25A | 175-490 | 75 | 94 | 2 | 73.7 | 74.9±1.2 |
| SAR13-25B | 185-490 | 75 | 89 | 6 | 76.0 |        |</p>
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SAR23-16B  180-490  75  89  1  80.4
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SAR23-17A  225-490  75  88  4  76.9  78.2±1.3
SAR23-17B  260-485  75  77  6  79.4

VAN07, Vanves, Rue Gaudray, [650-750] AD, (14/13/5)*
VAN07-04  VAN07-04A  220-500  75  93  7  75.4  75.6±0.3
VAN07-04B  175-490  75  91  3  75.5
VAN07-04C  240-490  75  88  5  76.0
VAN07-05  VAN07-05A  175-500  75  91  -3  74.2  73.1±1.1
VAN07-05B  175-500  75  90  4  72.0
VAN07-06  VAN07-06A  175-500  75  86  -4  76.4  76.7±1.3
VAN07-06B  225-490  75  73  4  78.1
VAN07-06C  255-500  75  79  8  75.5
VAN07-08  VAN07-08A  250-500  75  89  7  75.2  75.7±0.5
VAN07-08B  250-500  75  94  5  76.1
VAN07-09  VAN07-09A  185-500  75  86  1  74.5  73.6±1.0
VAN07-09B  195-500  75  88  7  72.6

A36/SAR08, Saran, Zac des Vergers, [675-725] AD, (43/29/9)*
A36-03  A36-03A  380-520  70  89  0  74.5  73.9±0.6
A36-03B  360-520  70  87  1  73.3
A36-05  A36-05A  390-485  65  69  6  69.3  68.2±1.1
A36-05C  355-500  70  80  4  67.1
SAR08-05  SAR08-05A  205-485  70  87  6  75.5  73.8±1.7
SAR08-05B  180-480  70  91  2  72.1
SAR08-13  SAR08-13A  335-480  70  79  4  72.3  72.5±0.2
SAR08-13B  385-495  70  77  -3  72.7
SAR08-18  SAR08-18A  180-515  70  94  -1  75.9  76.7±0.8
SAR08-18B  185-500  70  92  2  77.4
SAR08-19  SAR08-19A  225-500  70  96  4  71.0  71.4±0.4
SAR08-19C  265-495  70  95  5  71.7
SAR08-23  SAR08-23A  250-500  70  96  5  74.7  74.6±0.5
SAR08-23B  240-470  70  86  4  74.1
SAR08-23C  205-465  70  80  5  75.1
SAR08-33  SAR08-33A  215-500  70  91  3  72.6  72.9±0.3
SAR08-33B  235-470  70  77  3  73.1
SAR08-34  SAR08-34A  195-500  70  98  4  76.6  77.0±0.4
SAR08-34B  225-470  70  83  2  77.4

SAR25, Saran, La Guignace, [750-800] AD, (9/9/5)*
SAR25-01  SAR25-01A  175-495  75  90  2  80.2  80.2±0.1
SAR25-01B  190-485  75  86  2  80.1
SAR25-02  SAR25-02A  195-495  75  91  -3  73.2  73.5±0.3
SAR25-02B  176-495  75  89  -1  73.8
SAR25-04  SAR25-04A  175-500  75  94  3  79.4  79.4±0.0
SAR25-04B  175-485  75  90  4  79.4
SAR25-05  SAR25-05A  175-495  75  89  2  75.2  76.0±0.8
SAR25-05B  175-485  75  87  -6  76.7
SAR25-06  SAR25-06A  175-495  75  85  0  81.1  80.8±0.4
SAR25-06B  175-485  75  91  1  80.4

SAR26, Saran, La Guignace, [750-800] AD, (12/8/4)*
SAR26-01  SAR26-01A  175-495  75  98  4  73.2  73.3±0.1
| SAR26-02 | SAR26-02A | 180-500 | 75 | 94 | 0 | 73.4 | 74.2±0.8 |
| SAR26-02B | 175-490 | 75 | 91 | -1 | 74.9 |
| SAR26-06 | SAR26-06B | 225-520 | 75 | 94 | 5 | 75.0 | 75.0±0.0 |
| SAR26-06C | 225-520 | 75 | 94 | 4 | 75.0 |
| SAR26-08 | SAR26-08A | 270-485 | 75 | 75 | 5 | 78.0 | 78.2±0.2 |
| SAR26-08B | 280-500 | 75 | 85 | 7 | 78.4 |

**SAR07, Saran, Zac des Vergers, [775-825] AD, (30/23/6)**

| SAR07-01 | SAR07-01B | 195-515 | 75 | 83 | 0 | 78.4 | 77.4±1.0 |
| SAR07-01C | 175-530 | 75 | 90 | -3 | 76.4 |
| SAR07-10 | SAR07-10A | 320-485 | 75 | 85 | 2 | 71.6 | 70.9±0.8 |
| SAR07-10B | 355-480 | 75 | 85 | -3 | 70.1 |
| SAR07-19 | SAR07-19A | 175-500 | 75 | 93 | -3 | 79.6 | 80.0±0.4 |
| SAR07-19B | 175-480 | 75 | 88 | -2 | 80.3 |
| SAR07-21 | SAR07-21A | 255-505 | 75 | 94 | -4 | 77.6 | 78.1±0.5 |
| SAR07-21B | 255-480 | 75 | 83 | 5 | 78.5 |
| SAR07-23 | SAR07-23A | 175-500 | 75 | 93 | 1 | 78.2 | 78.2±0.0 |
| SAR07-23B | 175-485 | 75 | 85 | -2 | 78.2 |
| SAR07-26 | SAR07-26A | 230-480 | 75 | 82 | 3 | 75.2 | 77.0±1.8 |
| SAR07-26B | 270-470 | 75 | 75 | 2 | 78.7 |

**SAR05, Saran, Zac des Vergers, [800-850] AD, (24/22/5)**

| SAR05-03 | SAR05-03B | 345-540 | 80 | 96 | -2 | 77.8 | 78.3±0.5 |
| SAR05-03D | 310-540 | 80 | 91 | 3 | 78.7 |
| SAR05-06 | SAR05-06A | 175-515 | 80 | 96 | -4 | 82.4 | 82.8±0.4 |
| SAR05-06B | 175-490 | 80 | 83 | -1 | 83.1 |
| SAR05-11 | SAR05-11A | 175-520 | 80 | 94 | -6 | 75.4 | 76.3±0.9 |
| SAR05-11B | 175-485 | 80 | 85 | -2 | 77.1 |
| SAR05-13 | SAR05-13A | 310-515 | 80 | 80 | 0 | 78.4 | 77.2±1.2 |
| SAR05-13C | 335-505 | 80 | 83 | -2 | 76.0 |
| SAR05-19 | SAR05-19A | 180-480 | 80 | 88 | 4 | 77.1 | 77.0±0.1 |
| SAR05-19B | 175-470 | 80 | 82 | 1 | 76.9 |

**SAR27, Saran, La Guignace, [800-850] AD, (14/14/7)**

| SAR27-01 | SAR27-01A | 175-495 | 80 | 86 | -3 | 79.8 | 78.7±1.1 |
| SAR27-01B | 175-495 | 80 | 88 | 7 | 77.6 |
| SAR27-03 | SAR27-03A | 190-475 | 80 | 93 | 0 | 80.8 | 79.0±2.0 |
| SAR27-03B | 175-475 | 80 | 87 | 5 | 77.1 |
| SAR27-05 | SAR27-05A | 295-495 | 80 | 81 | 2 | 83.2 | 82.8±0.4 |
| SAR27-05C | 280-495 | 80 | 76 | 2 | 82.4 |
| SAR27-07 | SAR27-07A | 335-495 | 80 | 82 | 0 | 74.0 | 74.1±0.1 |
| SAR27-07B | 335-495 | 80 | 83 | 1 | 74.1 |
| SAR27-09 | SAR27-09B | 175-510 | 80 | 87 | -1 | 81.5 | 81.8±0.3 |
| SAR27-09C | 190-510 | 80 | 87 | 0 | 82.0 |
| SAR27-10 | SAR27-10A | 235-495 | 80 | 90 | 7 | 77.4 | 78.1±0.7 |
| SAR27-10B | 200-485 | 80 | 87 | 4 | 78.8 |
| SAR27-13 | SAR27-13A | 290-495 | 80 | 65 | 5 | 86.3 | 86±0.4 |
| SAR27-13B | 325-520 | 80 | 76 | 7 | 85.6 |

**A38, Saran, Lac de La Medecinerie, [800-850] AD, (6/5/2)**

| A38-03 | A38-03B | 295-505 | 80 | 97 | 7 | 81.8 | 81.1±0.7 |
| A38-03C | 255-510 | 80 | 97 | 6 | 80.4 |
| A38-06 | A38-06B | 175-470 | 80 | 92 | 1 | 79.5 | 79.9±0.4 |
| A38-06B | 175-465 | 80 | 89 | 2 | 80.2 |

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